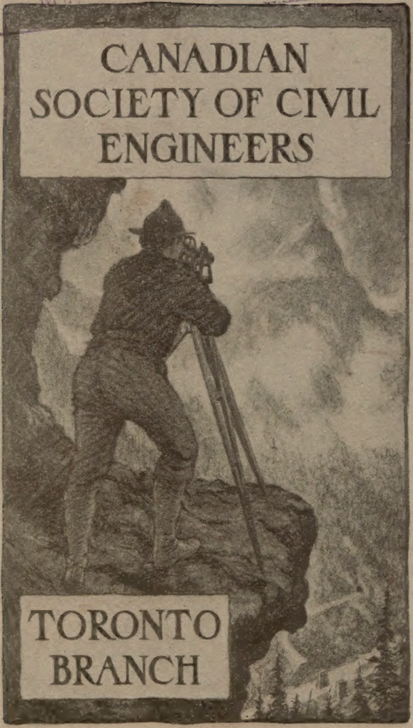
UNIVERSITY OF TORONTO
3 1761 01374280 4

627
UNIVERSITY OF TORONTO
DEPARTMENT OF CIVIL ENGINEERING
Structural



PROPERTY OF
TORONTO BRANCH
ENGINEERING INSTITUTE
OF CANADA
No.

UNIVERSITY OF TORONTO
DEPARTMENT OF CIVIL ENGINEERING
Municipal and Structural

a

LONGMANS'
CIVIL ENGINEERING SERIES

NOTES ON DOCKS AND DOCK CONSTRUCTION.

By C. Colson, C.B., M.Inst.C.E., Deputy Civil Engineer-in-Chief, Loan Works, Admiralty. With 365 Illustrations. Medium 8vo, 21*s*. net.

CALCULATIONS IN HYDRAULIC ENGINEERING: a Practical Text-Book for the Use of Students, Draughtsmen, and Engineers.

By T. Claxton Fidler, M.I.C.E., Professor of Engineering, University College, Dundee.

Part I. Fluid Pressure, and the Calculation of its Effects in Engineering Structures. With numerous Illustrations and Examples. Medium 8vo, 6*s*. 6*d*. net.

Part II. Calculations in Hydro-Kinetics. With numerous Illustrations and Examples. Medium 8vo, 7*s*. 6*d*. net.

RAILWAY CONSTRUCTION.

By W. H. Mills, M.I.C.E., Engineer-in-Chief, Great Northern Railway of Ireland. With 516 Illustrations. Medium 8vo, 18*s*. net.

PRINCIPLES AND PRACTICE OF HARBOUR CONSTRUCTION.

By William Shield, F.R.S.E., M.Inst.C.E., and Executive Engineer, National Harbour of Refuge, Peterhead, N.B. With 97 Illustrations. Medium 8vo, 15*s*. net.

CIVIL ENGINEERING AS APPLIED IN CONSTRUCTION.

By Leveson Francis Vernon-Harcourt, M.A., M.Inst.C.E. With 368 Illustrations. Second Edition, revised by Henry Fidler, M.Inst.C.E., F.G.S. Medium 8vo, 16*s*. net.

SANITARY ENGINEERING WITH RESPECT TO WATER-SUPPLY AND SEWAGE DISPOSAL.

By Leveson Francis Vernon-Harcourt, M.A., M.Inst.C.E. With 287 Illustrations. Medium 8vo, 14*s*. net.

TIDAL RIVERS: their (1) Hydraulics, (2) Improvement, (3) Navigation.

By W. H. Wheeler, M.Inst.C.E. With 75 Illustrations. Medium 8vo, 16*s*. net.

NOTES ON CONSTRUCTION IN MILD STEEL: Arranged for the Use of Junior Draughtsmen in the Architectural and Engineering Professions.

By Henry Fidler, M.I.C.E., Author of the Article on "Dockyards" in the *Encyclopædia Britannica*, and Editor of "Notes on Building Construction." With Illustrations from Working Drawings, Diagrams, and Tables. Medium 8vo, 16*s*. net.

LONGMANS, GREEN, AND CO.
LONDON, NEW YORK, BOMBAY, AND CALCUTTA

LONGMANS' CIVIL ENGINEERING SERIES

PRINCIPLES AND PRACTICE

OF

HARBOUR CONSTRUCTION

Digitized by the Internet Archive
in 2007 with funding from
Microsoft Corporation

http://www.archive.org/details/principlespracti00shieuoft

LONGMANS' CIVIL ENGINEERING SERIES

PRINCIPLES AND PRACTICE
OF
HARBOUR CONSTRUCTION

BY

WILLIAM SHIELD, F.R.S.E.

MEMBER OF THE INSTITUTION OF CIVIL ENGINEERS, AND FORMERLY EXECUTIVE
ENGINEER NATIONAL HARBOUR OF REFUGE, PETERHEAD, N.B.

WITH ILLUSTRATIONS

NEW IMPRESSION

SEEN BY
PRESERVATION
SERVICES
DATE JAN 30 1992

LONGMANS, GREEN, AND CO.
39 PATERNOSTER ROW, LONDON
NEW YORK, BOMBAY, AND CALCUTTA
1910

UNIVERSITY OF TORONTO
DEPARTMENT OF CIVIL ENGINEERING
Municipal and Structural

LIBRARY
NOV 1 1967
UNIVERSITY OF TORONTO

PREFACE

THE object of this work is to set forth the general principles which should govern the design and construction of harbours, and to describe the various types of breakwaters and the methods of constructing them usually adopted in modern practice.

Drawings of different kinds of breakwaters, including some of the more prominent existing works, are given; and, in addition to these, numerous diagrams and sketches have been introduced wherever it has been considered they would be useful in elucidating the descriptions given in the text.

The chance of successfully opposing an enemy depends much upon knowledge, previously obtained, respecting his strength and mode of attack, and of the means and materials available for purposes of defence. It is, therefore, of importance that the harbour-engineer should be well informed respecting the forces against which he will have to contend, and also that he should possess an accurate knowledge of the structure and properties of the different materials which are available for use in harbour construction. The subjects of wind, waves, tides, currents, and materials have therefore been treated of at some length; and attention has also been directed to the more important physical conditions which affect harbour construction.

"The wide range of subjects which the profession of a civil engineer embraces, renders it imperative on every member of it to avail himself of all the help he can obtain.

"The personal experience of one individual cannot fit him for the exigencies of a profession which is ever extending its range of subjects, and is constantly dealing with new and complex phenomena; consequently, nothing is more certain than that he who wishes to reach the perfection of his art must avail himself of the experience of others as well as of his own, and that he will not unfrequently find both little enough to guide him" ("Presidential Address of the late Sir John Hawkshaw to the Members of the Institution of Civil Engineers," *Min. Proc. Inst. C.E.*, vol. xxi.).

If this be true—as it undoubtedly is—of the profession of civil engineering generally, it is eminently so of that admittedly difficult branch of it which deals with sea-works. I therefore feel that I need offer no apology for having consulted numerous works, or for having collected information from all available sources, in compiling the present volume. It is not, however, a mere compilation of knowledge derived from the writings of others, for it includes the results of my own research, and of experience which I have gained in the course of a practice extending over a period of well-nigh thirty years.

In consequence of my time having been very fully occupied by my professional duties, much of what I have written has been jotted down in a somewhat fragmentary manner; and at times many weeks, and even months, have elapsed without my having been able to write anything at all, or even to put my notes into shape. I therefore beg the indulgence of my readers, and trust they will deal leniently with me for all my shortcomings.

I have endeavoured, by footnotes or otherwise, to record the various sources from which I have gleaned information, but I fear that in some instances I may have inadvertently omitted to do so; I now therefore very gratefully acknowledge my indebtedness to all those whose works I have consulted in the preparation of this book, and I also tender my sincere thanks to my professional brethren and others who have kindly furnished me with much valuable information, which could not have been obtained from other sources.

WILLIAM SHIELD.

Peterhead, N.B.,
1895.

THE following is a list of the principal books which have been consulted in the preparation of this work :—

"Weather." Abercromby.
"The Law of Storms and of Variable Winds." Reid.
"The Law of Storms." Dove.
"The Physical Geography of the Sea and its Meteorology." Maury.
"Elements of Geology." Lyell.
"Temple of Serapis." Babbage.
"Tides and Waves." Airy (Excerpt "Encyclopædia Metropolitana.")
"Tides." Whewell and Lubbock (*Philosophical Transactions*, 1833.)
"Encyclopædia Britannica."
"Chambers's Encyclopædia."
Minutes of Proceedings of the Institution of Civil Engineers.
"Harmonic Analysis of Tidal Observations." Baird and Darwin (*Minutes of Proceedings of the Royal Society*, vols. xxxix. and xlv.)
Transactions of the Royal Society of Edinburgh.
Minutes of Proceedings of the International Maritime Congress, 1893.
"Notes on British and Foreign Harbours." Rennie.
"Harbours and Docks." Harcourt.
"The Design and Construction of Harbours." Thos. Stevenson.
The various Blue Books containing Reports of Commissions on Harbours, etc., 1845–1884.
Report of Committee on the Employment of Convicts in the United Kingdom, 1882.
Report of Committee appointed by the Board of Trade to inquire into the question of Electrical Communication between Light-vessels and outlying Lighthouses and the Shore, 1887.
"Building Construction," Part III.
"Handbook for Surveyors." Hurst.
"Chambers's Journal."
"Civil Engineering." Rankine.
"Voyage of the *Challenger*." Thomson.
"Blasting and Quarrying of Stone." Burgoyne.
"The Ice Age in North America." Wright.
"Engineering."

CONTENTS

CHAPTER I.

WIND.

PAGE

Wind the generator of sea-waves—Working season—Wind diagrams—Direction and velocity of wind—Cyclones—Anti-cyclones—Extent of storm areas—Progress of storms—Wind-gauges—Relation of wind-velocity to Pressure—Relative frequency of gales on the British coasts—Forecasting gales—Monsoons—Significance of clouds, etc.—Lunar rainbows—Halos—Rollers arriving before gale—Harbour entrances and direction of littoral drift affected by wind—Arresting wind-blown sand . 1

CHAPTER II.

WAVES.

Knowledge of waves necessary in designing sea-works—Experiments on waves—Movement of particles in waves—Waves of oscillation—Waves of translation—Breaking waves—Length of waves—Depth to which wave-action extends—Effect of breakwater mounds upon waves—Cresting waves—Velocity of waves—Earthquake waves—Free waves—Ground-swell—Forced waves—Height of waves—Impact of waves—Wave-action on beaches 23

CHAPTER III.

TIDES.

Theory of tides—Spring tides—Neap tides—Tidal wave never perfectly formed—Priming and lagging of tides—Effect of variations in distance of sun and moon, also of declination—Diurnal and semi-diurnal tides—Equinoctial spring tides—Summer and winter tides—Progress of the tidal wave—Tidal range in Bay of Fundy, Bristol Channel, etc.—Tidal range in open ocean—Tides in Mediterranean Sea—Double tides—Tides at Batsham—Tidal "establishment"—Tidal harmonic analyzer—Mechanical prediction of tides—Harmonic analysis of tidal records—Effect of wind upon tides—Effect of atmospheric pressure upon tides—Effect of tidal range upon sea-works—Use of, and facilities afforded by, tidal range—"Bore" 44

CHAPTER IV.

CURRENTS.

PAGE

Origin of ocean currents—Evaporation and precipitation—Water-circulation in Mediterranean and similar seas—Effect of wind on currents—Temporary currents caused by wind—Currents running counter to prevailing winds—Tidal currents—"Races" or "roosts"—Velocity of littoral currents increased by breakwaters projected across them—Effect of currents upon height of waves—Strong currents out of harbours objectionable . . 63

CHAPTER V.

FETCH, EXPOSURE, AND WAVE-POWER.

Definition of "Fetch"—Fetch alone no indication of exposure—Wheeling of waves—Direction of waves affected by contours of sea-bed—Exposure of sites affected by shift of wind and by scour during gales—Glacial action mistaken for wave-power—Movement of earth's crust in relation to apparent effects of wave-power—Raised beaches—Ruins of temple of Jupiter Serapis—Effect of waves on coast near Wick; also at Holburn Head, Caithness—Effect of falling water—Evidences of wave-power in Zetland—Wave-power as displayed at Ymuiden, Kurrachee, Wick, Alderney, Scilly Isles, Wolf Rock lighthouse, etc.—Mud as an indication of exposure—General remarks on exposure of sites 73

CHAPTER VI

QUARRYING.

Selection of quarry site—Overburden—Drainage—Arrangement of quarries—Height of working face—"Strike" and "dip" of strata—Small-hole blasting—Weight of charges—Mine-blasting—Line of least resistance—Cranes, etc.—Steam and hand drilling—Consumption of steel—Forms of drills—Explosives—Seam-firing—Cutting stone by means of "plugs" and "feathers"—Charging bore-holes—Tamping—Firing by electricity—Lightning fuse—Safety fuse 89

CHAPTER VII.

MATERIALS.

SECTION I.

General remarks—Erosion—Eroding agents—Power of moving shingle—Sand-blast—Danger of open joints in structures 105

SECTION II.—STONE.

Stone for sea-works should have high specific gravity—Basalt, granites, and syenites—List of stones—Indications of decay—Chalk, limestones, and sandstones—*Pholas dactylus*—Quartzite—Weathering qualities of stones—Iron-furnace slag used for constructing breakwaters 110

SECTION III.—CONCRETE.

Early use of concrete—Value of concrete in sea-works—Hydraulic lime—Proportion of ingredients in concrete—Mixing by hand—Mixing by machines—Concrete-block making—Roman-cement concrete—Medina cement—Stone-faced blocks—Blocks built of rubble in cement mortar . . . 113

SECTION IV.—CEMENTS.

PAGE

Portland cement—Analyses of clay and chalk—Process of making Portland cement—Air-slaking—Porosity in concrete—Indications of good Portland cement—Rate at which Portland-cement briquettes gain strength with age—Apparent decrease of strength at age of seven or eight months—Analysis of good Portland cement—Roman cement—Medina cement . 124

SECTION V.—TIMBER.

Various kinds of timber used in sea-works—Destruction of timber by sea-worms, etc.—*Teredo navalis*—*Limnoria terebrans*—*Chèlura terebrans*—Methods of preserving timber—Greenheart, sneezewood, and jarrah repel sea-worms—Creosoted Baltic red-wood, oak, and teak useful in some localities—Pitch pine quickly attacked by sea-worms—Greenheart and jarrah liable to split—American rock elm useful for fendering—Black ironwood eaten freely by *Teredo navalis* 131

SECTION VI.—IRON AND STEEL.

Durability in sea-water—Records differ widely—Results of experiments—Effect of galvanic action—Structural and chemical differences affect rate of corrosion—Simple corrosion—Rate of corrosion of plates, etc., of s.s. *Gambia*—Effect of exposure on castings at Bell Rock lighthouse, on wrought-iron rails at Port Elizabeth, on ironwork of piers at Ramsey and Port Elizabeth, and on ironwork of beacon at Wolf Rock—Beardmore on decay of iron—Wrought iron more durable than cast iron in sea-water—Mallet on preservation of iron—Redman on decay of iron—Pier at Milton-on-Thames—Gravesend town pier 138

CHAPTER VIII.

CONSIDERATIONS AFFECTING THE GENERAL DESIGN OF HARBOURS.

No general rules for designing harbours can be laid down—Preliminary investigation—Survey—Materials available for works—Quarry and work-yard sites—Transport of materials—Description of vessels to be provided for—Beaching ground—Spending-beaches—Future development of port—Degree of shelter required—Anchorage—Good and bad holding-ground—General requirements of harbours of refuge—Natural features of sites should be utilized 146

CHAPTER IX.

ESTUARY HARBOURS—GROUND PLANS OF HARBOURS—ENTRANCES.

Estuary harbours—"Bars"—Lagoons—Removal of "bars"—Concentration of ebb current—Importance of large tidal compartment—Protection of ebb current—Site of entrance—Maintenance of depth—Relative value of upland and tidal waters—Borings on site of proposed entrance, etc.—Physical and nautical requirements often opposed to each other at harbour entrances—Ground plans of harbours—Wave expansion—Direction of main entrance—Parallel jetties—Isolated breakwaters—Harbours with two entrances—Roadsteads—Advantages of deep water at entrance—Strong current across harbour entrance objectionable—Widths of entrances—Reduction of waves—Relative advantages of embayed and salient sites for harbours 150

CHAPTER X.

FISHERY HARBOURS.

PAGE

Difficulty of designing small harbours—Injury inflicted upon boats by "range"—Inner basins and spending-beaches—"Booms"—Entrances—Risks incurred in entering tidal or barred harbours—Fish deteriorate by delayed delivery—Berthage—Quay space—Water area—Loss incurred for want of proper harbour accommodation—Dimensions and equipment of herring fishing-boats 165

CHAPTER XI.

VARIOUS TYPES OF BREAKWATERS.

Classification of breakwaters—Vertical types—Mound types—Action of waves against vertical faces—Timber-framed breakwaters—Breakwaters with side walls of masonry and hearting of loose rubble—Kilrush pier—Wick breakwater—Danger of loose rubble hearting—Advantages of using large blocks in constructing breakwaters—Breakwaters formed of concrete blocks laid in horizontal courses—Defects of system—Batter undesirable—Stone facing—Breakwaters formed of blocks resting on base of mass-concrete—Monolithic system of construction—Methods of depositing concrete under water—Causes of failure—Concrete bag-work—Fraserburgh breakwater—Wave-breaker—Breakwaters of blocks laid in sloping courses—Advantages of system—Colombo, Mormugão, and Manora (Kurrachee) breakwaters—Large blocks used at Réunion—Mound breakwaters—Angles of slopes indicative of extent of exposure—Plymouth, Kingstown, Table Bay, and Portland breakwaters—Pitched slopes—Disturbance of rubble by wave-action—Holyhead breakwater—Madras breakwater—Sorting rubble for breakwater mounds—Cause of trouble at Plymouth breakwater—Alderney breakwater—Causes of failure—Mounds of pell-mell blocks on rubble bases—Mounds of rubble, faced and capped with pell-mell blocks—Mounds of pell-mell blocks, backed with rubble—Mounds of pell-mell blocks with superstructures—Rubble mound with pell-mell block facing and superstructure—Economy and advantages of using large blocks—General observations on rubble and concrete block mounds—Failures of pell-mell block breakwaters—Particulars relating to various pell-mell block breakwaters—Rubble mound breakwaters, faced and capped with stepped blocks in courses—Particulars of cost, rate of progress, maintenance, etc., of various existing breakwaters . . . 172

CHAPTER XII.

PIER-HEADS.

Necessity for strengthening the ends of piers—Range along harbour side of piers—Various types of pier-heads—Pier-head lights and fittings . . 222

CHAPTER XIII.

WAVE-SCREENS AND FLOATING BREAKWATERS.

Designs for wave-screens and floating breakwaters based upon wrong hypotheses—Description of wave-screens proposed by Hays, Scott, and Calver—Floating breakwaters—Examples of, in nature—Icebergs—Weed-fields—Size of effective floating breakwater—Behaviour of vessels riding at anchor—Impossibility of mooring floating breakwaters—Inefficiency of floating breakwaters—Booms at harbour mouths—Floating-weed type of breakwater—The mooring of lightships 225

CHAPTER XIV.

DIFFERENT METHODS OF CONSTRUCTING BREAKWATERS.

PAGE

Staging—Barges—Cranes or over-end setting-machines—Facilities afforded by staging in constructing rubble-mound breakwaters—Holyhead breakwater staging—Sea-staging of ordinary type—Mode of depositing rubble at Holyhead—Mode of constructing Alderney breakwater—Aberdeen breakwater staging—General remarks on staging—Facilities afforded by staging in building block-work, etc.—Cost of staging—Rubble mounds formed by means of barges—Advantages of steam-barges—Bags of concrete, also concrete blocks, placed by barges—Barges and staging compared—Various types of setting-machines—Block-lifting appliances—Diving—Mound breakwaters constructed by over-end tipping . . . 236

CHAPTER XV.

FOUNDATIONS.

Founding upon rock—Difficulties attending execution of work near low water—Benching rock—Steeply inclined strata—Advantages of staging as compared with over-end machines in preparing foundations—Underwater mass-concrete foundations—Levelling foundations with small broken stone—Grouting—Founding upon sand—Curved profiles—Mud—Pilework foundation—Founding upon gravel—Founding upon clay—Founding upon rubble mounds 257

CHAPTER XVI.

SETTLEMENT AND BOND.

Settlement can seldom be altogether avoided—Usually greatest in breakwaters of mound type—Increased by weight of superstructure—Unequal settlement—Weight of heavy setting-machines injurious to new work—Settlement of breakwaters at Holyhead, Alderney, Colombo, Mormugão, and Manora (Kurrachee)—Bond—Objections to—Vertical bond—Evils attending "dry bedding" of blocks—Objections to "stretchers"—Dowels—Notching—Tabling—Dovetailing—Absence of bond in Manora breakwater—Sloping coursed work accommodates itself to settlement—Bond of block-work in Tynemouth breakwaters 275

CHAPTER XVII.

SILTING.

Process described—Wave and current action—Effect of piers projected from the shore—Advance of foreshore—Prolongation of jetties—Dredging—Sluicing—Harbours on sandy coasts—Outlying isolated breakwaters—Direction of drift 284

UNIVERSITY OF TORONTO
DEPARTMENT OF CIVIL ENGINEERING

CHAPTER I.

WIND.

Wind the generator of sea-waves—Working season—Wind diagrams—Direction and velocity of wind—Cyclones—Anti-cyclones—Extent of storm areas—Progress of storms—Wind-gauges—Relation of wind velocity to pressure—Relative frequency of gales on the British coasts—Forecasting gales—Monsoons—Significance of clouds, etc.—Lunar rainbows—Halos—Rollers arriving before gale—Harbour entrances and direction of littoral drift affected by wind—Arresting wind-blown sand.

Since wind is the generator of ordinary sea-waves, almost all the troubles which beset the construction of sea-works are attributable to it.

It is not possible to foretell the advent of heavy seas, except by forecasting the wind which produces them;[1] those in charge of sea-works will therefore do well to anticipate gales, to the best of their ability, and by taking such precautionary measures as may be deemed necessary, or as may be within their power to adopt, prepare in time for the heavy seas which they know the wind will bring up. Work should also be arranged so as to take advantage of what is usually termed the "working season," being that part of the year during which gales are least frequent and the sea smoothest.

This period will be found to vary much on different coasts, according to the extent and direction of their exposure; and in different parts of the world, according to the season of the year.

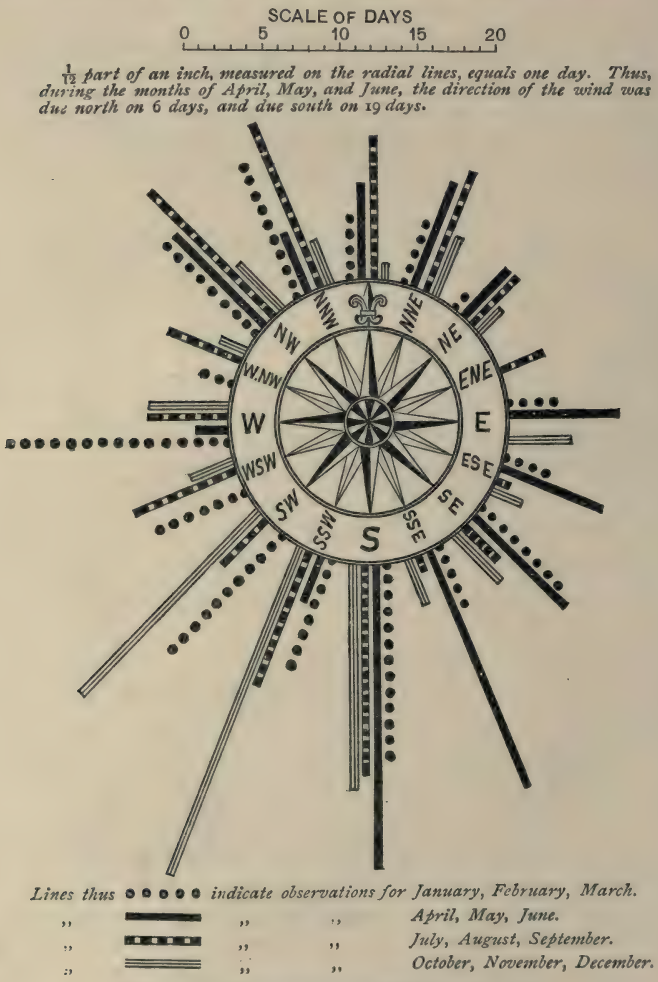
The direction of littoral drift is, in the great majority of cases, determined almost solely by that of the prevailing winds; and there are other considerations, to which reference will be made in the sequel, which render a knowledge of the general direction, strength, duration, relative frequency and sequence of the winds prevailing in any locality where the construction of sea-works is contemplated, very necessary.

---

[1] In regard to swell sometimes preceding storms, see pp. 19, 20.

I propose, therefore, in this chapter, to direct the reader's attention to that section of meteorology which treats of wind, as having a direct and important bearing upon the main subject of this work.

Diagrams, constructed so as to show at a glance the prevailing daily direction and force of winds, extending over as long a period as possible—which should, at the least, embrace one whole year—will be found useful in considering any design for sea-works. The patterns of such diagrams are multiform, but the following (Figs. 1 and 2) are given as examples.

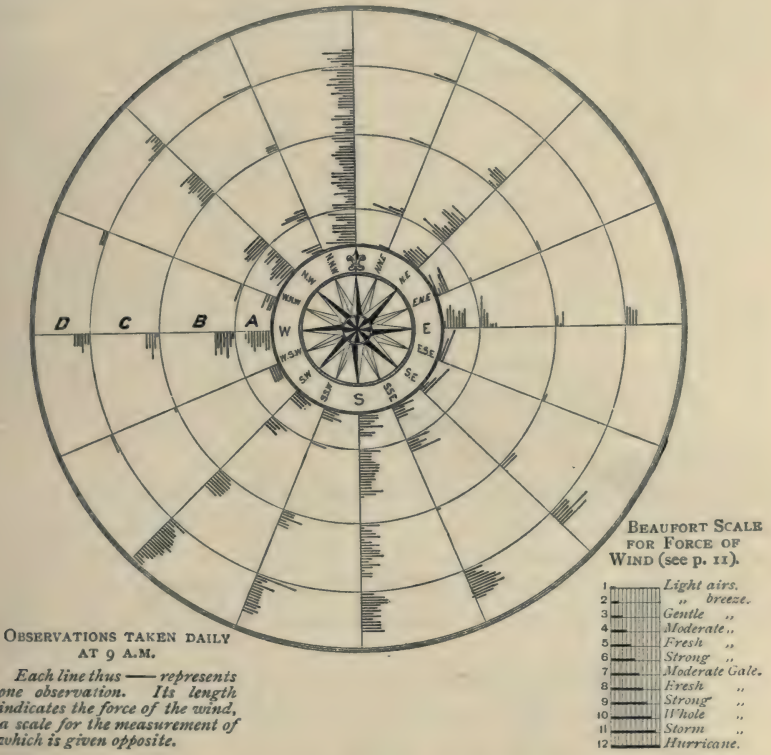


$\frac{1}{12}$ part of an inch, measured on the radial lines, equals one day. Thus, during the months of April, May, and June, the direction of the wind was due north on 6 days, and due south on 19 days.

Lines thus ● ● ● ● ● *indicate observations for January, February, March.*
" ━━━━ " " *April, May, June.*
" ▬ ▬ ▬ " " *July, August, September.*
" ════ " " *October, November, December.*

FIG. 1.—Wind diagram for Peterhead, year 1889.

The form of diagram represented in Fig. 1 shows, fairly well, the direction and relative frequency of prevailing winds at different periods of the year; but it lacks one most essential feature, inasmuch as it gives no indication of the force of the wind. Thus, it may show that, say, southerly winds are the most prevalent in any given locality, while it altogether fails to show that those possibly from the south-east, although less frequent, blow with the greatest violence. This is an all-important point for the harbour engineer to be correctly informed upon, and, with the view of supplying this deficiency, I, many years ago, designed the form of diagram shown in Fig. 2, which explains itself.



BEAUFORT SCALE FOR FORCE OF WIND (see p. 11).

OBSERVATIONS TAKEN DAILY AT 9 A.M.

Each line thus —— represents one observation. Its length indicates the force of the wind, a scale for the measurement of which is given opposite.

FIG. 2.—Wind diagram for Peterhead, year 1888. Each zone embraces observations for three months. Zone A, January, February, March; Zone B, April, May, June; Zone C, July, August, September; Zone D, October, November, December.

Such diagrams may be amplified by showing the limits of exposure of any site which may be under consideration, the direction of the heaviest waves, and so forth.

If it should be desired to show the winds separately for each month, it will be found convenient to distinguish the several months by means of colours instead of zones. Thus, for instance, the observations for January, February, and March may be shown by three shades of green; April, May, and June, by three shades of red; July, August, and September, by three shades of brown; and October, November, and December, by three shades of grey.

In order to show to how great an extent the relative frequency of certain winds may vary from year to year, and the consequent necessity for obtaining information which embraces as long a period as practicable, I have compiled the foregoing diagrams from observations taken at Peterhead during two different years.

The generally accepted theory of wind is so well known that I shall not occupy the time of the reader by describing it here.[1] Suffice it to say that the never-ceasing effort of the atmosphere to equalize temperature and restore lost equilibrium all over the globe, and the rotation of the earth, are the two principal forces which affect the direction and velocity of the main atmospheric currents.

There are, however, many minor forces or influences at work, which produce changes in the direction and velocity of the wind; such, for example, as the variation of day and night temperature, the distribution and trend of land, mountain chains, clouds, ocean currents, drift ice, and even the contact of one aërial system with another.

Ocean currents, being slow to part with heat, and being often thrown far out of the courses they would naturally pursue, by the irregular distribution of land and other physical conditions, affect, to a very great extent, the temperature of the atmosphere along their course.

A change in the temperature of the air is synonymous with a change in its pressure; consequently, if the air in any locality should be warmed, and thus rarefied by contact with a warm ocean-current, an upcast aërial current will at once be formed, and the colder air from surrounding districts will flow in to re-establish equilibrium. Thus variations in temperature, occurring in different localities, create currents, counter-currents, and eddies, which resolve themselves into those cyclonic and anti-cyclonic movements to which the atmosphere seems ever prone. Associated with these we find V-shaped areas of low pressure, "wedges" of high pressure, and so forth.

---

[1] The subject is very fully treated in a book to which I shall hereafter refer, viz. "Weather," by Hon. Ralph Abercromby (Kegan Paul & Co.).

Since an ascending current is composed of light air, which is therefore indicated by a low barometer, wind always blows in upon a centre of low pressure. This it does, with but few exceptions,[1] in a spiral form.

The reverse takes place around areas of high pressure or anti-cyclones.

Cyclones are analogous to upcast shafts, drawing the air inwards at the bottom, and throwing it outwards at the top; while anti-cyclones are analogous to downcast shafts, drawing the air inwards at the top, and dispersing it outwards at the bottom.

Vertical scale one-half.

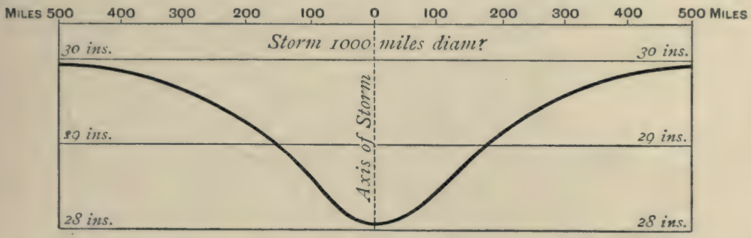


Fig. 3.—Diagram[2] of mean barometric curve across the centre of the great Cuba hurricane, transversely to its path, October 4 to 7, 1844. The mean barometric curve on the centre line of the path of the storm appears not to have differed essentially from the above.

Cyclones are indicative of bad weather and high winds, and, in the northern hemisphere, revolve in the reverse direction to the hands of a watch; whereas anti-cyclones are associated with fair, calm weather or light winds, and revolve in the opposite direction. In the southern hemisphere, the direction of rotation, both of cyclones and anti-cyclones, is reversed.

In Fig. 3, a barometric section of a storm-basin, or cyclonic depression, is indicated.

The areas of storm-basins are sometimes very great, measuring not unfrequently from 1000 to 1500 miles across, and seldom being less than 600 miles. In such systems, however, the inner or more dangerous portion is of much smaller proportions, probably not exceeding 200 to 250 miles in diameter.

---

[1] *E.g.* the trade winds, monsoons, electrical disturbances, and what are termed "straight-line gales."

[2] Copied from Reid's "Law of Storms," p. 312.

A typical cyclone, having its centre over England, is represented in Fig 4.

The rate of the progress of storms, *i.e.* of the cyclonic areas, varies considerably. At times their forward movement does not amount to more than 2 or 3 miles per hour, while at other times they travel at from 40 to 50 miles per hour; 17 to 25 miles per hour seems to be a common rate for European storms.

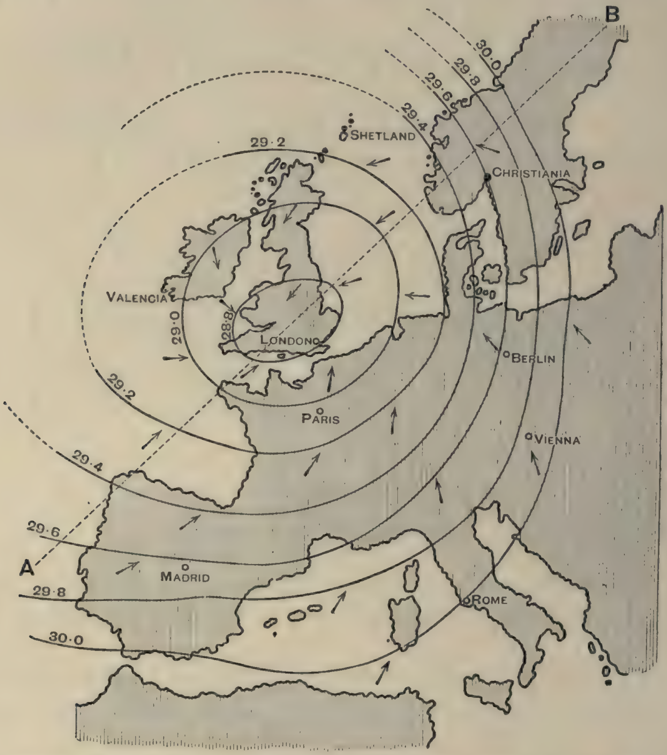


FIG. 4.—Diagram of typical cyclone. The arrows indicate the direction of the wind. The curved lines are isobars, or contours of equal barometric pressures, varying, in this case, from 28·8 inches at the centre of the storm to 30 inches at its outer limit.

Tropical cyclonic hurricanes generally travel at a slower speed, but rotate at a much greater velocity than extra-tropical ones.

The progressive motion does not indicate either the direction or velocity of the wind, both of which are quite independent of the course along which, or rate at which, the storm advances.

It would, therefore, be erroneous to imagine that the velocity of the wind during a gale, multiplied by the duration of the gale, would give a correct idea of the extent of such disturbance ; otherwise a gale of, say, three days' duration, with an average velocity of 50 miles per hour, would have travelled a distance of 3600 miles, whereas the actual distance traversed would probably not exceed one-third of this, or it might even be very much less.

The direction and velocity of wind are most conveniently recorded by means of graphic wind-gauges, or anemographs, in which a slewing motion, for indicating direction, is combined with the ordinary cup anemometer by means of tangent screws actuated by fans.

The lines indicating direction and velocity are drawn upon a paper attached to a cylinder, which derives its motion from clockwork.

Some of these machines give continuous diagrams, so that the direction and velocity of the wind at any moment during the day or night may be read off at leisure.

Another description of wind-gauge is that in which pressure, instead of velocity, is recorded; but as yet these have not proved at all reliable.

Relation of Wind Velocity to Pressure.

At first sight, it would appear an easy matter to establish a comparison between the velocity of wind and the pressure exerted by it; nevertheless, up to the present time no satisfactory method of doing this has been devised.

The chief difficulty seems to lie in the fact that the apparent pressure per unit of area varies with almost every size and form of surface against which the wind impinges. This is doubtless in a great measure due to the varying degree of vacuum which the wind current creates in the rear of the objects acted upon. However this may be, all the best authorities on the subject are agreed that, at present, there exists no satisfactory method of establishing a relation between wind velocity and pressure; indeed, it seems doubtful if such a comparison be possible.

I cannot do better than here quote what Abercromby says on this subject in his excellent work before referred to. On p. 202, he states as follows:—

"The velocity of wind is a real quantity, which is perhaps capable of measurement in the abstract, though we are at present far from being able to gauge it accurately. But it is quite certain that there is no such thing as an absolute force which corresponds to a given velocity.

"According to the theory of stream-lines, when even an inelastic fluid meets an obstacle, if the angles of the obstruction do not break the continuity of the fluid, so as to form eddies or vortices, the same amount of pressure which is imposed on the body by the first deflection of the fluid is given back again as the stream-lines of the fluid close up behind the obstruction. For instance, if a ship is lying at anchor in a current, the same amount of strain which the current causes on her cable when forced asunder by the bows, is given back when the current closes in behind her; so that the total pressure which she experiences is only that due to the friction of the water on her skin. This is, of course, on the supposition that her lines are so easy that they do not break the stream-lines so as to form little eddies or vortices.

"Now, the same thing holds with wind. If we put up two square plates of different sizes, face to the wind, the pressure on each is not proportional to the area, while in light breezes neither will record anything. The reason is that, in light wind, a thin mobile fluid like air can glide round even the sharp angles of a square without forming eddies, and as there is no vacuum formed behind the plate, there is no pressure recorded. In higher winds the stream-lines are broken, and every shape and every sized plate of the same shape form a different series of eddies round the rim of the obstacle. Then the amount of rarefication behind the various plates is neither identical nor proportional, and therefore every shape and size of anemometer indicate discordantly at every different velocity.

"From all this, it follows that, though we might say that the pressure on a board one foot square was twenty pounds, and might compare this force with that on another board of the same size and mounting, we should not be justified in saying that the force of the wind was twenty pounds per square foot in the abstract, because a board ten feet square, even if of the same shape, would have given a different number."

As further bearing on this subject, I quote the following from Hurst's "Handbook for Surveyors" (14th edit., p. 140):—

"RESISTANCE OFFERED TO THE WIND BY BODIES HAVING THE SAME CROSS-SECTION, BUT OF VARIOUS SHAPES (FROM HUTTON'S 'EXPERIMENTS').

	Proportional numbers.
Cone, vertex towards the wind	126
,, base to the wind	291
Sphere	124
Cylinder, end to wind	285
Hemisphere, flat side	288
,, round side	119

The careful records which were kept at the Forth Bridge works have done much to throw light upon this difficult subject. The results obtained from the wind-gauges at these works during a severe south-west gale, which occurred in November, 1888, are recorded in *Chambers' Journal* of January 26, 1889, from which I quote as follows :—

"The severity of the gales in November last (1888), as measured by the recording instruments at the Forth Bridge, affords ample evidence of the intensity of one of the most prolonged storms that have been felt in Scotland for many years. The worst of these gales was that which began early on the morning of the 16th of November, and continued with but little intermission into the morning of the 17th. The wind blew from the south-west; and those in charge of the Forth Bridge believed that, though blowing very hard on Friday, the gale was, if anything, more severe in the early hours of the following morning.

"The Forth Bridge wind-gauges, situated on the old Castle of Inchgarvie, are three in number. The large gauge presents an area of three hundred square feet to the wind, and is fixed parallel to the centre line of the Forth Bridge, being specially designed and erected to test the pressure of wind over a larger area than that of the gauges commonly in use. This gauge registered at 9 a.m. on the 17th of November, for the previous twenty-four hours, a maximum pressure of twenty-seven pounds per square foot. The small pivoted gauge, which has an area of only one and a half square foot, and which, by means of a vane, is always made to stand at right angles to the direction of the wind, indicated a pressure on the same day of thirty-five pounds per square foot; whilst the gauge of similar dimensions, but rigidly fixed with its face parallel to the centre line of the bridge, registered on the same date forty-one pounds per square foot, a pressure corresponding to a velocity of wind exceeding ninety miles per hour.

"It will be noted that the pressure per square foot on the large gauge is considerably less than on the smaller gauges. This reading corresponds with all previous experience at the Forth Bridge, and would seem to indicate that the pressure on the small gauges must be due to 'threads of air' of limited area and high velocity, which, when integrated over a large surface, produce an average pressure of considerably reduced intensity."

The foregoing agrees closely with information which the resident engineer at the Forth Bridge works (Mr. F. E. Cooper, M. Inst. C.E.) kindly furnished to me.

Notwithstanding the foregoing generally admitted facts, it may be useful to give the pressures which are commonly associated with wind velocities, as it is likely these will continue to be adopted until some better method of computing them than at present exists has been discovered.

For convenience of reference, I have therefore incorporated these in Fig. 5.

The pressures represented by the full curved line are those usually associated with the relative wind velocities. In view of the uncertainty which surrounds this subject, they must, however, only be taken as approximately correct.

The most recent investigations tend to show that the usually accepted wind pressures—at all events, when applied to large areas—are too high, and that those indicated by the dotted curve are probably the more accurate.

The following particulars, relative to the great storm of November 17 and 18, 1893, were issued from the Meteorological Station at Deerness, Orkney:—

"A hurricane of unprecedented violence passed over the north of Scotland on the evening of the 17th and morning of the 18th. The hurricane commenced exactly at 6 p.m. like the shot of a gun, and during the first hour reached a velocity of 77 miles—the previous hour being only 14—and attained its maximum velocity from nine to ten at the rate of 95 miles, seven miles stronger than any one previously recorded from Orkney. The weather for the week previous was extremely fine for November, although some indication of the fearful hurricane was given by the gradual falling of the barometer, which on the 11th, at 9 p.m., had reached the unusually high figure of 30·563 corrected, and gradually fell till 1 p.m. on the 17th, when it reached the minimum of 28·599. After that, owing to the approaching north wind, it gradually rose again. The barometric readings corrected are—11th, 9 p.m., 30·563; 16th, 9 p.m., 29·368; 17th, 9 a.m., 28·747; 17th, 9 p.m., 28·757; 17th, 1 p.m., 28·599.

This hurricane was preceded by, and accompanied with an excessive rainfall and high thermometer, which is invariably the case with well-marked cyclonic depressions. The rainfall for the 24 hours from 9 a.m., 17th, to 9 a.m., 18th, was 1·55 inch, the highest for several years. If we include the 12 hours previous to this, we have 36 hours with the heavy rainfall of 2·13 inches. The maximum reading of the thermometer on the forenoon of the 17th was 48·8—this high figure being caused by reduced pressure and atmospheric saturation.

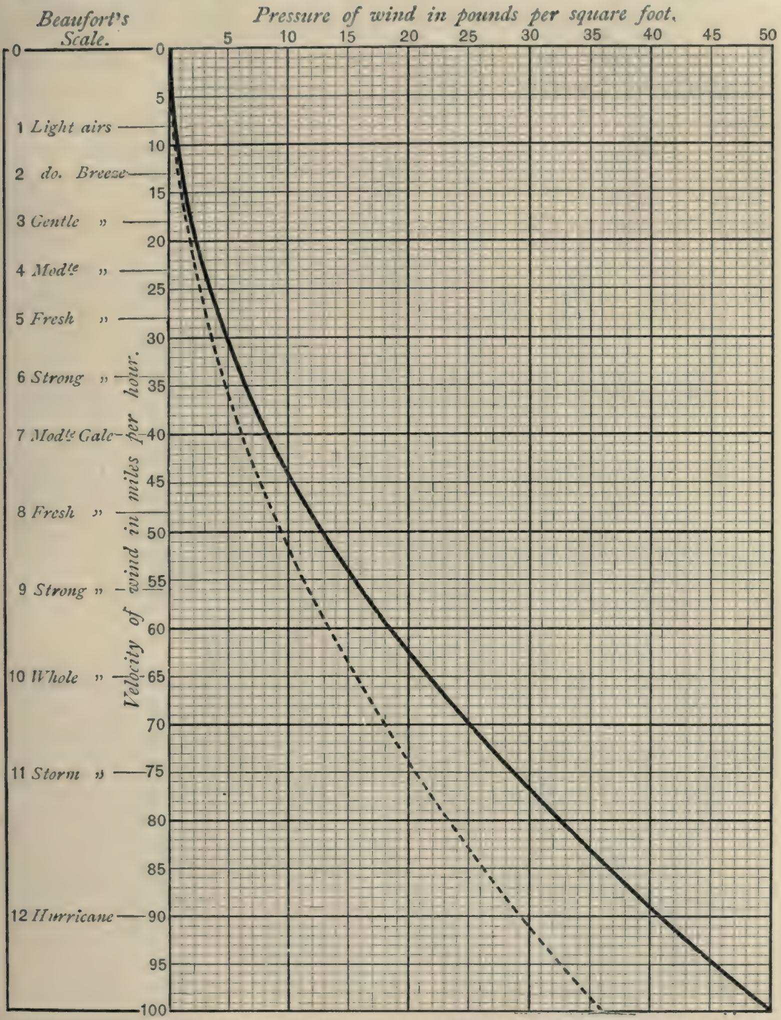


Fig. 5.—Diagram of relative wind velocities and pressures.

UNIVERSITY OF TORONTO
CIVIL ENGINEERING

At 9 p.m. it had fallen to 39·0, and at 9 a.m., 18th, to 30·5—a variation in temperature of 18 degrees in 24 hours. The annexed table shows the force and direction of wind as recorded by Robertson's anemograph, with estimated wind pressure in pounds per square foot as calculated by Sir Henry James, Director of Ordnance Survey.

Hour and date.	Direction of wind.	Velocity.	Pressure.
17th 11 a.m.	S.S.E.	26	3½
12 „	S.E.	23	2¾
1 p.m.	S.E.	21	2¼
2 „	S.E.	17	1½
3 „	E.S E.	14	1
4 „	E.S.E.	11	⅝
5 „	E.	14	1
6 „	N.	77	29¾
7 „	„	84	35½
8 „	„	91	41½
9 „	„	95	45¼
10 „	„	92	42½
11 „	„	94	44¼
12 midnight.	„	94	44¼
18th 1 a.m.	„	87	38
2 „	„	83	34½
3 „	„	80	32
4 „	„	80	32
5 „	„	74	27½
6 „	„	70	24½
7 „	„	68	23¼
8 „	„	68	23¼
9 „	„	60	18

From the above it will be noticed that, taking the velocity for 15 hours from 6 p.m., 17th, to 9 a.m., 18th, the average rate is 82½ miles, which, for duration and high velocity, has probably not been surpassed in Great Britain. The following are dates of gales with velocity over 80 miles experienced in Orkney since 1863:—

Date.	Direction of wind.	Max. velocity.
1869—February 27	N.W. by W.	81 miles.
1877—November 16	W.	83 „
1882—January 6	W.	82 „
1884—January 20	W. by S.	88 „
1885—February 21	S. by E.	82 „
1893—November 17	N.	95 „

Attempts have been made to construct empirical formulæ, based upon the average of a great number of observations, by which the height of waves may be deduced from the velocity of the wind. It is, however, impossible to establish any reliable comparison between them.

At best the results obtained could only be average results, the variations on either side of which must of necessity be very great, inasmuch as, even assuming practically unlimited fetch[1] and depth of water, the duration of the gale, and the variations in its direction, not only at the point of observation, but along the whole line of fetch—or, at all events, along that portion of it traversed by the gale—form most important yet unobtainable factors.

The subject of waves will, however, be considered in the next chapter.

RELATIVE FREQUENCY OF GALES ON THE BRITISH COASTS.

In a paper which was read by Mr. R. H. Scott, Secretary to the Meteorological Office, at one of the conferences in connection with the Health Exhibition of 1884, it was shown from an analysis of daily records, which had been taken during fourteen consecutive years, commencing April, 1870, that the total number of severe gales, of the force of 9 and upwards (Beaufort Scale, p. 11), which occurred on the coasts of the British Isles during that period was 379; and that they were distributed over the several months in the following proportions.

Month.	Average number during 14 years.	Average number for each year.
January	71	5·07
November	58	4·14
October	55	3·93
March	47	3·36
December	47	3·36
February	46	3·28
September	18	1·28
April	17	1·21
August	11	0·79
May	4	0·29
June	3	0·21
July	2	0·14

It would thus appear that the periods about the vernal and autumnal equinoxes are not those which are most to be dreaded, as many persons are in the habit of supposing.

---

[1] See p. 73.

FORECASTING GALES.

If simultaneous readings of the barometer are available from a number of stations, embracing a sufficiently large area—as is now the case in many places by means of the electric telegraph—contours, or lines of equal barometic pressure, termed "isobars," may be plotted upon a chart. These will, for the most part, be found to arrange themselves around high or low pressure centres in an approximately circular or elliptical form (see Fig. 4, p. 6).

Such an arrangement, when it embraces a low-pressure centre, is termed a "cyclone;" when a high-pressure one, an "anti-cyclone."

The contours will also form what are known as "V's" of low pressure, "wedges" of high pressure, etc.

Diagrams constructed in this manner are called "synoptic" or "synchronous" charts. They usually contain information respecting temperature, direction and velocity of wind, clouds, and weather generally.

Upon the form and movement of these atmospheric systems, or arrangements of isobars, almost the whole science of weather-forecasting depends. Apart from other indications, they show the force and direction of the wind which may be expected in any part of their path, inasmuch as the force or velocity of the wind varies in proportion to the *rate* of the gradient, which is shown by the relative closeness of the isobars to each other. The velocity is always greatest where the gradient is steepest. Storms are only ordinary winds intensified by the steepness of such gradients.

The direction of the wind is generally that of the contours, only it is more or less spirally incurved or inclined towards the centre in cyclones, and outcurved from the centre in anti-cyclones. This inclination varies considerably, making under some conditions an angle of upwards of 50° with the isobars, and in other cases being very small indeed.

These gigantic eddies move about the globe without following any very certain course; but their probable direction and speed, as indicated by that portion of their course already traversed, may generally be surmised by a study of consecutive synoptic charts, always providing that the area embraced by them is of sufficiently large extent.

It is only by a study of such charts that forecasts, with a pretension to accuracy, can be made. Notwithstanding this, however, a solitary observer, by making use of all the indications at his disposal, may often make a very good guess at what the weather is going to be.

The first step towards this is to carefully record the movements of the barometer and thermometer, which, if possible, should be self-recording instruments.

The indications given by these, coupled with the observation of clouds, and a consideration of the usual local sequence of weather under varying conditions, will often enable fairly correct forecasts to be made. Such forecasts are, however, obviously not so reliable as those emanating from a study of charts, like those just described.

Since—as has already been pointed out (see Fig. 3, p. 5)—the central, and at the same time the most dangerous, part of a storm is a low-pressure area, it follows that as such area approaches the barometer will fall; and since the velocity of wind is proportionate to the barometric gradient down which it blows, if successive readings of the barometer, on being plotted, show a convex curve or increasing *rate* of fall, the violence of the gale may be expected to increase. If, on the contrary, a concave curve or decrease in the *rate* of fall is indicated, the wind may be expected to moderate.

A quickly falling barometer—inasmuch as it indicates a steep gradient, which is synonymous with high wind velocity—almost invariably forebodes bad weather.

There is a law in meteorology, known as "Buys Ballot's law," which is as follows: "Stand with your back to the wind, and the lowest pressure will always be on your left hand in the northern hemisphere, and on your right in the southern hemisphere." Thus the position of a storm centre may be approximately determined.

The manner in which the wind either veers or backs as a storm advances depends upon the position which the observer occupies in the cyclonic area. Thus, wind in the northern hemisphere appears to back if the observer is stationed to the left of the centre line of the storm's path, and to veer if to the right of such line. This will be evident on reference to Fig. 4, p. 6, it being assumed that the storm is travelling along the line AB in the direction of B. In the southern hemisphere the converse of this obtains.

If the observer should happen to be on the centre line of the storm's path, the wind will appear to "jump" right round, it may be, say, from north-east to south-west.

In Northern Europe cyclones rarely pass so far to the south as to give the backing sequence; but when they do they are almost always soon followed by another cyclone and fresh bad weather.

Along the north-east coast of Scotland, the wind usually backs from south-west round by south to south-east in the worst gales; whereas along the west coast of Holland, it generally veers from south-west round by west to north-west.

Notwithstanding that the course of storms cannot be predicted with certainty, they appear, in the majority of cases, to follow generally the direction of the predominant aërial currents in which they are embedded, in much the same way that eddies in a river follow the course of the stream, except when deflected by obstructions or other influences. Hence in the North Atlantic and over Great Britain, and other parts of Northern Europe, the course of storms is generally easterly or north-easterly, *i.e.* from west to east, or south-west to north-east. In consequence of this, warning of their approach can often be telegraphed from America several days before they arrive.

In the Mediterranean many of the storms travel southward, being no doubt drawn in that direction by the ascending current of hot air over Northern and Central Africa. Unlike those further north, very few seem to travel to the eastward. In the South Atlantic and Indian Oceans, they usually work round from south-west to south-east or east.

In many countries periodical winds and sequences of weather recur with such regularity that forecasting is a simple matter. Amongst such, monsoons are perhaps the most noteworthy. These occur over the area occupied by the Indian Ocean, and embrace the East Coast of Africa, India, Ceylon, etc.

The south-west or warm wet monsoon prevails from April to October; and the north-east or cold dry monsoon, from October to April. Somewhat similar periodic winds also prevail off the coasts of Brazil and Mexico.

It is generally considered that monsoons are mere modifications of the "Trades." Vast tracts of land and sea, becoming periodically heated by the sun's rays, produce ascending currents which induce an inflow of denser air from the surrounding regions. Thus in summer, when the sun is vertical over the northern part of India, an upcast or cyclonic system prevails in that region, causing an indraught, and thus giving rise to the southerly monsoon; whereas in winter, such region being at midday about 47° north of the path of the sun, and its temperature thus much reduced, a downcast or anti-cyclonic system with its outflowing currents takes the place of the cyclone, and gives rise to the northerly monsoon.

Although from habit, and probably also from the fact of barometers being usually marked "rain," "change," "fair," "very dry," and so forth, many persons have accustomed themselves to associate the relative heights at which the mercury stands with wet or dry weather, the barometer, as a matter of fact, is influenced only by the weight of the atmosphere, which, as has already been shown, depends chiefly upon its temperature. If, therefore, a barometer be placed under the influence of light air which has traversed the ocean and become laden with moisture, the mercury will stand at a low level, on account of the lightness of the atmosphere, and at the same time will indicate rain, simply because the wind from that quarter happens to have acquired moisture, as just described.

If, on the other hand, a barometer be placed, say, in the midst of a vast tract of dry warm land or desert, the rarefied air from this will cause it to fall, but a low barometer under such conditions would not indicate rain. Therefore it is evident that the movements of a barometer must be interpreted with due regard to the physical conditions which surround it.

It is, however, not always easy to determine these. Indeed, it is almost impossible to do so, with any degree of certainty, except by the help of synoptic charts.

From what has just been said, the reader will doubtless be prepared to find temperature rising as a storm approaches. This is usually what happens; indeed, the trace or diagram of the thermometer's movements is often roughly that of the barometer inverted. Still, this must not be taken as a universal rule. In northern latitudes the barometer rises and the thermometer falls for northerly gales, while the converse indicates wind from the southward.

The form assumed by the surface of the mercury in a barometer tube shows which way the mercury is inclined to move. If inclined to rise, the surface is convex; if to fall, concave. This arises from the friction or adhesion of the mercury to the sides of the tube. As the *tendency* of the mercury is usually a more sensitive indication than the actual level at which it stands, this point is worthy of notice.

The significance of different kinds of clouds depends much upon their surroundings, so the value of conclusions arrived at from their study will naturally be in proportion to the experience and local knowledge of the observer.

Different forms of cloud have, however, from long observation, been popularly associated with certain kinds of weather. For instance, cirrus cloud, of the kind known as "mares' tails," "sea-grass," etc., is a pretty certain indication of wind, especially if its movement be rapid.

This cloud always occupies a high position, so its drift is indicative of the direction and velocity of the upper wind currents, and deserves careful attention.

Hard cumulus to seaward, showing over a dark haze, often presages a gale. This must, however, be distinguished from the rocky detached summer cumulus, which in many parts is associated with fine weather; as are also soft-looking, fleecy clouds, or cirro-cumulus.

Abercromby, in speaking of cloud prognostics, says that what is known as "festooned cumulus" is usually followed by a severe gale in Orkney, whereas similar clouds in Lancashire are only considered a sign of rain.

Small hard stratus clouds, such as are frequently seen at sunset, are indicative of fine weather, while soft-looking, heavy stratus usually degenerates into nimbus or rain-clouds. Stratus clouds, however, from the conditions necessary for their formation and existence, seldom indicate wind.

It will be seen that, as clouds have not the same significance in all localities, or under all conditions, it is not possible to lay down any laws regarding them which shall be universally applicable. The inference to be drawn from various forms and movements of clouds, as well as from other symptoms in any locality, may, however, soon be learnt by a little careful observation, and by noting the sequence of weather associated with them. Such a knowledge, coupled with the readings of the barometer and thermometer, will be valuable aids to forecasting to those who may happen to be in remote places, where they have not the advantage of the telegraphic warnings issued by a meteorological office.

I may here mention, as an example of a purely local cloud prognostic, one which is a pretty reliable indication of a south-east gale at the Cape of Good Hope. The atmosphere there, during and in advance of south-east gales, is heavily charged with moisture. When, therefore, a gale is approaching, this vapour is condensed on coming into contact with Table Mountain, and hangs about its flat top as a white cloud of a form which has earned for it the name of "Table-cloth." Thus when the "Table-cloth" is seen upon Table Mountain, you may be pretty sure a south-east gale is not far distant. A somewhat similar cloud hangs about the rock of Gibraltar, with an easterly wind blowing up the Mediterranean, notwithstanding that the sky at the time may be blue and clear.

Another indication, which at the Cape foretells the approach of a "south-easter," is an exceptional transparency in the water of the ocean. I am quite unable to suggest any reason for this.

Lunar rainbows, or halos, or a hazy moon with a falling barometer, are almost certain signs of wind.

A bright yellow sky at sunset, a red sky in the morning, and what is termed a "high dawn," or when the sun rises over a bank of clouds, are also indications usually associated with bad weather; while a rosy sky at sunset, whether clouded or clear, a grey sky in the morning and a low dawn, or when the first signs of dawn appear on the horizon, generally indicate fine weather.

Waves or rollers, coming in without any apparent cause, as frequently noticed by those engaged on sea-works, are often forerunners of a gale. They may, however, as elsewhere described, be only swell set up by a distant gale which does not blow home.

In regard to swell preceding a storm, Reid cites a notable case, as follows:—

> "I was in Bermuda when the hurricane of September 8 to 14, 1839, occurred, and distinctly heard the sea breaking loudly against the south shores on the morning of September 9, full three days before the storm reached the islands, as recorded in tables of the state of the weather kept at the central signal station.

"At that time the hurricane was still within the tropic, and distant ten degrees of latitude.

"As the storm approached the swell increased, breaking against the southern shores with louder roar and greater grandeur, until the evening of September 12, when the whirlwind storm, reaching the Bermudas, set in there. When the storm had passed over the Bermudas, the southern shore became calm, and the northern reefs, in their turn, presented a white line of surge."[1]

It would be out of place were I, in this volume, to pursue the subject of forecasting weather further. Much progress has been made of late years in the science of meteorology, but it can scarcely yet be called an exact science.

The reader will, however, find much valuable information on this subject contained in the book, to which I have already referred, entitled "Weather," by the Hon. Ralph Abercromby (Kegan Paul and Co.), which he cannot do better than peruse. I have found it of much service, and am indebted to it for many of the facts recorded in this chapter.

Winds, apart from their action in forming waves, affect harbours in other ways.

Due attention must, for instance, be given to the direction of prevailing gales in determining the position, direction, form, and width of harbour entrances; otherwise an entrance may be so placed as to be difficult or dangerous for a vessel to take during a gale, or it may form a trap for littoral drift.

A badly designed entrance will often lead heavy seas into a harbour, thereby causing a dangerous "run" and inconvenient range.

The usual sequence of winds should also be considered, in order that, as far as possible, the convenience of vessels getting to sea as soon as the wind has shifted into a more favourable quarter may be provided for.

The drift along the coast is, in the majority of cases, very largely due to wind, and to the waves set up by its action. The angle at which these impinge upon the shore will be found, in most cases, to determine the direction of its travel, the preponderance of drift, one way or the other, usually bearing a very marked relation to the direction of prevailing winds.

Drifts above the water-line, on sandy shores, proceed concurrently with those caused by wind waves below such level;

---

[1] "Law of Storms and Variable Winds," chap. iv. p. 36.

and they not unfrequently play a prominent part in choking up bays, estuaries, or river channels.

The rapidity with which such drifts will sometimes form banks against or around objects impeding their course is remarkable; and the advance of foreshores is often much accelerated by the accumulations thus deposited about piers or jetties which cross sandy shores.

On many coasts—notably those of France and Africa—the expenditure incurred in arresting these sand-drifts has been very large. The object aimed at is to prevent the sand being blown, or, as it is termed, to "fix" it, for a sufficient length of time to admit of the growth of vegetation in such luxuriance as to form a natural covering to the surface, and so protect it from the wind.

The system usually adopted is that of spreading cut brushwood[1] over the whole area of the drift—commencing, as a matter of course, at the windward end—and sowing the seed of various suitable plants.

Sometimes the brushwood, instead of being used to cover the surface, is employed in forming artificial hedges or "breakwinds." These are constructed by sticking the brushwood into the sand, so as to form parallel hedges about 4 feet in height. They are generally placed from 10 to 12 feet apart, and run at right angles to the course of prevailing winds. Seeds of different trees, and of various suitable plants and grasses, are then sown and raked in, young trees being also planted.

At the Cape of Good Hope, aloes, cut down and stuck into the sand, quickly take root, and form excellent hedges. Where these cannot be obtained, brushwood which retains its leaves when dead should be selected.

Care must be taken that the sowing of seeds and planting of trees is carried on at the right season.

The system of forming hedges is more costly than that of merely spreading the brushwood, but it possesses the great advantage of affording protection to young plants and trees until they have acquired sufficient strength to take care of themselves.

Sometimes palisades formed of planks are used, the planks being driven sufficiently far into the sand to give them stability, and being spaced so as to allow openings of two or three inches between them. A bank of sand quickly collects on the leeward and windward sides of such barriers, and if, as the height of the bank increases, the boards be raised by drawing them a few feet at a time, very large quantities of sand may be thus arrested, and high mounds formed.

[1] In some instances town refuse has been employed with advantage.

Another system, which in some localities has been quite successful, and which is probably the least costly of any, is that of planting roots or tufts of sand-loving grasses about 18 inches apart over the area to be reclaimed.

Perhaps the best of these is the sea-reed (*Ammophila arenaria*), which frequents the dry loose sand of the sea-shore. The runners of this grass, which throw out roots from every joint, and from which new shoots proceed, push their way in all directions through and over the sand, and soon form quite a network.

Several other kinds of grasses may be planted with advantage, as, for instance, sea-wheat (*Triticum junceum*), purple fescue (*Festuca rubra*), upright sea-lyme (*Elymus arenarius*), etc.

One great advantage which grasses possess is that the wind, by bending their stems, lays them close to the sand, and thus causes them to afford the maximum amount of protection just when it is most needed.

In some extensive sand-drifts in the Cape Colony in which I was interested, in connection with harbour work, willows (Port Jackson and golden), maritime pine, blue gum, tobac plant, protea, waxberry creeper, bloembosch, Kaffir fig, wild cotton, and several kinds of grasses, were all used with more or less success.

Every effort should be made to induce the growth of trees, with the view of obtaining some return for the expenditure incurred. Some of the reclaimed sand-drifts of France, which were planted with maritime pines, now return a substantial revenue.

The average cost of reclaiming sand-drifts at the Cape was about £25 to £30 per acre.

Where a good supply of grass-roots can be readily obtained, the system of reclaiming drifts by planting them may, however, be carried on at a very much smaller cost.

CHAPTER II.

WAVES.

Knowledge of waves necessary in designing sea-works—Experiments on waves—Movement of particles in waves—Waves of oscillation—Waves of translation—Breaking waves—Length of waves—Depth to which wave-action extends—Effect of breakwater mounds upon waves—Cresting waves—Velocity of waves—Earthquake waves—Free waves—Ground-swell—Forced waves—Height of waves—Impact of waves—Wave-action on beaches.

THOSE who may be engaged in designing or constructing sea-works should, as far as possible, correctly understand the nature and action of sea-waves, because upon these the principles which regulate the various designs for breakwaters and similar works are to a great extent based.

I propose, in considering this branch of our subject, to avoid abstruse mathematical investigations, and to confine my remarks within such limits as, I hope, may be of practical use.

The theory of wind-waves, or undulations upon water, has been very fully gone into by the late astronomer royal, Sir G. B. Airy; also by the Messrs. Weber, Robertson, Scott Russell, and others.

The Webers and Scott Russell, during their inquiries, carried out elaborate experiments, the results of which are valuable for comparison with those obtained by the aid of mathematical science, with which, it is satisfactory to find, they very closely agree.

The Webers conducted their experiments in long troughs, the sides of which were made of glass. In these troughs water was placed which contained numerous coloured particles having the same specific gravity as the water. By watching these minutely when waves were made to traverse the water, the motion of the particles in every part of any wave, as well as in the water below it to its full depth, was clearly seen and carefully noted.

Scott Russell's experiments—as recorded in the report of the seventh meeting of the British Association—were conducted on somewhat similar lines to those of the Webers, inasmuch as troughs having glass sides were used in each case. Those used by Scott Russell were, however, of much larger dimensions than those employed by the Webers, and very sensitive appliances were provided for observing and recording the heights and velocities of the waves, as also their shape, the movement of the particles forming them, and other points of interest.

It would be difficult to devise a more illusive spectacle than that presented by a series of large passing waves, it being almost impossible to divest the mind of the idea that the volume of water forming each wave is actually advancing.

In watching waves from some such position as a pier-head or staging, as they pass shoreward, this feeling seems to be intensified, the eye naturally following them in their course, and they retaining their individuality in a remarkable manner, until they finally break upon the shore.

If, however, instead of watching the waves themselves, we fix our attention upon some free object floating upon the surface, it will soon become evident that, instead of passing onward with the waves, it oscillates between certain points, the distance between which bears a fixed relation to the length of the waves between crest and crest.

Any onward movement of such floating object, which may be caused by the action of the wind upon it, or by any current which may exist, must, of course, be duly allowed for.

Theoretical investigations, supported by the carefully conducted experiments above referred to, show that the circulation of the particles of water in waves of oscillation is approximately that indicated by Fig. 6.

The long feathered arrow denotes the direction of propagation, and the shorter unfeathered arrows show the movement of the particles of water, which, in a wave of oscillation, is nearly such as would be produced by rolling circles, having their diameters equal to the height of the waves, trough to crest. The form of the waves is therefore approximately cycloidal.

It will be noticed that the particles in the troughs of the waves move backward, while those forming the upper portions of the waves move forward. The points indicated in the diagram by the letters A and B respectively are neutral points.

Those in the rear of the waves, as at A, are centres of departure for particles which are constantly leaving them and moving towards the points B on the faces or breasts of the waves. The backs or windward surfaces of the waves are thus being constantly lowered, through loss of water, whereas the fronts, or breasts, are being constantly raised by the flow of particles towards them. This lowering of the backs of the waves and heaping up of their fronts is, in deep water, little more than a vertical movement of the particles. The motion is, however, delusive, and causes waves to assume the appearance of moving bodily forward, and carrying with them a mass of water equal to their volume. It is, nevertheless, well known that only the form and energy of the wave are transmitted, and not the water, excepting to a certain extent in waves of translation, to which we will presently refer.

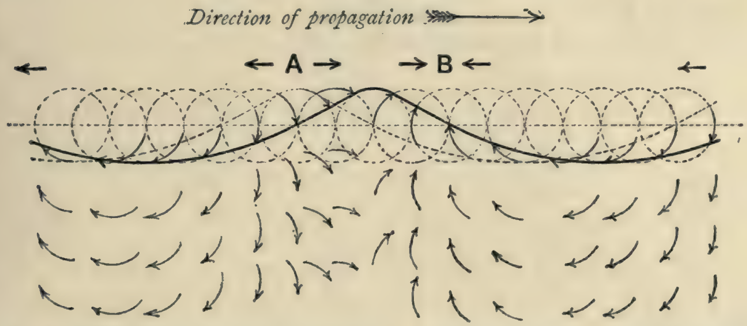


Fig. 6.—Diagram[1] showing motion of particles in a wave of oscillation. The small arrows indicate the motion of the particles which form the wave, and illustrate the manner in which they flow towards its breast and away from its windward surface, as described above.

As waves pass into gradually shoaling water the friction of the bottom becomes more and more felt by them, the motion of the particles of water in contact with the bottom being most retarded, and that of the others in a constantly diminishing degree towards the surface. This causes a gradual change to take place in the form of the waves, as shown by the sketch in Fig. 7, p. 26. Their slopes, back and front, become steeper, their crests more raised, and the orbits in which their particles revolve become elliptical. Such waves are passing, by degrees, from a state of approximate simple oscillation to one of more

---

[1] Copied, with some slight alteration, from a sketch which illustrates Sir G. B. Airy's treatise on "Tides and Waves."

UNIVERSITY OF TORONTO
DEPARTMENT OF CIVIL ENGINEERING
[illegible] and SURVEYING

and more intensified translation; and the particles are, in a constantly increasing degree, being carried forward by each successive wave. Finally, the bottom friction so retards the lower particles of the wave that the crest overruns the face slope, and the wave "breaks." At this moment, *i.e.* just as the wave is commencing to break, the forward motion of the particles is equal to the velocity of the wave, and the wave-stroke is delivered with its most destructive effect.

Although the length of such waves, from crest to crest, diminishes as they approach the shore, their period[1] remains constant. Therefore, seeing that a lesser distance is traversed in the same time, it follows that the velocity of waves diminishes with their length. Since, then, the velocity of waves is that which most affects their impact, long waves are more to be feared than shorter ones, notwithstanding that the latter may be of greater height.

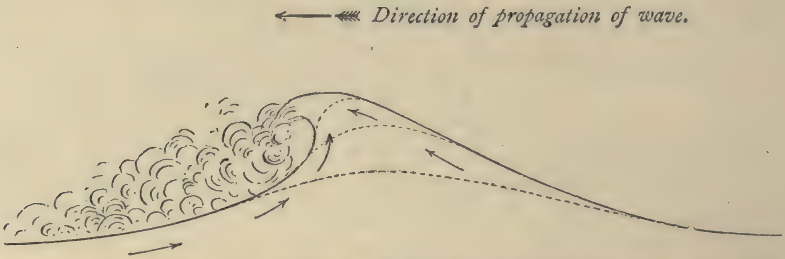


FIG. 7.—Breaking wave. The dotted lines indicate the successive forms which a wave assumes prior to breaking.

Waves whose length is small compared with the depth of water traversed by them, may, for all practical purposes, be considered as belonging to the class called "Oscillatory."

From what has been said, it will be seen that in water of a given depth small waves may be, or at any rate may closely approximate to, simple waves of oscillation; whereas in water of the same depth storm waves may assume the character of waves of translation, in consequence of their being so much more affected by bottom friction.

I mention this here as having reference to the effect of long rubble foreshores—such as those in the mound type of

[1] The period of a wave is the time occupied in its traversing a distance equal to its length. It is also equal to the time which the respective particles composing the wave take in performing one complete revolution.

breakwaters—upon the character of waves; but I shall again refer to this subject later on.

Sir G. B. Airy has shown[1] that when the depth of water is great as compared with the length of a wave—as in the case of ordinary waves in the open sea—each particle of water in an oscillatory wave describes a circle about its position of rest, in the vertical plane in which the wave is advancing. The motion of particles is therefore forward in that section of the wave which is above the normal water-level, and backward in that which is below it, and they attain their greatest respective forward and backward velocities when at the highest part of the crest and lowest part of the trough (see Fig. 6, p. 25).

The diameters of these circles rapidly decrease with increased depth of water, so that at a depth equal to the length of the wave, crest to crest, the motion of the water-particles is only $\frac{1}{535\cdot4}$ of that at the surface, whereas at double that depth it only amounts to $\frac{1}{286690}$ of that at the surface.

The motion thus diminishes in geometrical progression as the depth below the surface proceeds in arithmetical progression. Let the reader note, however, that the depth of water in which breakwaters are constructed seldom much exceeds one-tenth the length of the waves in heavy seas, at which depth the difference of the horizontal range of particles at the bottom, as compared with that at the surface, is but small.

The tables[2] on p. 28 give the greatest extent of horizontal and vertical displacement of the particles of water, at different depths, for waves whose length is equal to the depth of the water which they are traversing; and also for waves whose length is ten times as great as the depth of the water which they are traversing; the greatest horizontal displacement of the particles at the bottom being represented by 2.

Notwithstanding the rapid diminution in the motion of the particles from the surface downwards, the effect of the bottom upon passing waves is sufficient to cause them to break in considerable depths of water. This is more especially the case when an abrupt change of depth takes place.

There is a shoal, known as Riy Bank, off the south coast of Africa, where long ground-swell waves of moderate height, say 10 feet to 12 feet trough to crest, are commonly seen to break,

[1] "Tides and Waves."

[2] Extract from Table IV., Airy, "Tides and Waves."

the position of the bank being indicated for hours, or even days together, by a patch of white foam. The general depth of water upon this bank at low water is 10 fathoms, only one isolated point rising to within 6 fathoms of the surface.

TABLE 1.—LENGTH OF WAVE EQUAL TO DEPTH OF WATER.

Depth below the surface.	Horizontal displacement of particles.	Vertical displacement of particles.
At surface	535·429	535·425
$\frac{1}{10}$ whole depth	285·651	285·643
$\frac{2}{10}$ "	152·398	152·384
$\frac{3}{10}$ "	81·312	81·287
$\frac{4}{10}$ "	43·396	42·350
$\frac{5}{10}$ "	23·182	23·096
$\frac{6}{10}$ "	12·426	12·264
$\frac{7}{10}$ "	6·737	6·434
$\frac{8}{10}$ "	3·798	3·229
$\frac{9}{10}$ "	2·408	1·341
At bottom	2·000	0·000

TABLE 2.—LENGTH OF WAVE TEN TIMES AS GREAT AS DEPTH OF WATER.

Depth below the surface.	Horizontal displacement of particles.	Vertical displacement of particles.
At surface	2·408	1·341
$\frac{1}{10}$ whole depth	2·328	1·192
$\frac{2}{10}$ "	2·258	1·048
$\frac{3}{10}$ "	2·196	0·908
$\frac{4}{10}$ "	2·144	0·772
$\frac{5}{10}$ "	2·100	0·639
$\frac{6}{10}$ "	2·063	0·508
$\frac{7}{10}$ "	2·036	0·379
$\frac{8}{10}$ "	2·016	0·252
$\frac{9}{10}$ "	2·004	0·126
At bottom	2·000	0·000

During strong gales waves break upon the south-west end of the Dogger Bank, off the coast of Yorkshire, the depth of water upon that part of the bank varying from 7 to 10 fathoms.

As a further indication of the depth and extent to which storm-waves are felt, Sir John Coode states that he found the shingle of the Chesil Bank disturbed by wave action, during the heaviest winter gales, at a depth of 8 fathoms, the shingle thus disturbed being of large size.[1]

Captain Calver, R.N., observed that in gales of wind off the east coast of England, wave action was felt (as indicated by discoloration of the water) to a depth of 12 fathoms.

---

[1] Minutes of Evidence, Select Committee on Harbours of Refuge, 1857.

Mr. Murray mentions that shingle and chalk ballast—which would have a high specific gravity—thrown overboard from ships off Sunderland, at a distance of from 7 to 10 miles from shore, into water of at least 10 fathoms in depth, were brought ashore in large quantities during violent storms, and cast upon the beach by wave action.[1]

It is known that waves frequently break along the edge of the Bank of Newfoundland, in consequence of the depth of water there abruptly decreasing to about 80 fathoms. These waves, rolling in from the Atlantic, probably have a length of at least 1000 feet.

It will be evident, from what has been stated, that storm-waves, when traversing such comparatively shallow water as it is possible to construct sea-works in, must all, in a greater or less degree, be waves of translation; and, further, that the higher and longer waves are, the more dangerous they become, not only by reason of their increased volume, but because their translatory nature is proportionately more developed, and the forward motion of the water—being that which chiefly affects breakwaters—increased.

Small waves of oscillation may be seen dancing harmlessly up and down against the vertical wall of a breakwater or other upright face, whereas larger waves in the same position, having, by reason of their feeling the bottom, become waves of translation, strike the face with great violence, the measure of which is indicated by the volumes of water which are thrown up.

Seeing that the character of waves is thus changed for the worse as they proceed over a shoaling bottom, it follows that the long foreshores formed by the deposit of rubble mounds, as in the case of the Holyhead, Portland, Plymouth, and other breakwaters of similar design, cause this transformation to take place. In the two first-named breakwaters (Plymouth breakwater has no superstructure), the rubble mounds are for the most part carried up to or above the level of high water of spring tides. The waves therefore break upon the mound, and are to a great extent spent, so that they do not, in their solid form, reach the superstructure.

The height to which the rubble mound is carried in a composite breakwater, in relation to the levels of high and low water and to the magnitude of the waves, is of great importance.

---

[1] *Min. Proc. Inst. C.E.*, vol. xix. p. 670.

The breakwater at Alderney was[1] of the composite type, and the level to which the rubble mound was carried varied in different sections of the work. In the most exposed places, it was only carried up to, or perhaps it would be more correct to say maintained at, the level of 12 feet below low water of spring tides, and it sloped away to seaward at the rate of about 1 in 5½.

The range of spring tides at Alderney is 17 feet, and the seas are exceptionally heavy.

There can, I think, be no doubt that the violence with which they assailed the work was greatly increased by the slope of the rubble mound having been formed at the level it was.

In general, waves break on entering water the depth of which but little exceeds their height, trough to crest; therefore, at some period during each tide storm waves at Alderney would be made to break just as they reached the superstructure, and consequently just at the time when their greatest destructive power had been attained.

From observations which are recorded on p. 39, it will be seen that waves in Peterhead Bay, 26 feet in height, broke in passing the 5½-fathom line.

There were several features in the design of the Alderney breakwater which, since the days of its design, experience has shown to be objectionable, and which doubtless contributed to its destruction; but the one just referred to—intensifying, as it undoubtedly did, the destructive power of the waves—was probably the means of developing other defects, which under different circumstances might have remained latent.

The failure of this large work has taught engineers many instructive lessons, and the profession is indebted to Mr. L. F. Vernon-Harcourt, M.I.C.E., for having given, both in a paper which he contributed to the Institution of Civil Engineers,[2] and also in his work on "Harbours and Docks,"[3] a very full and interesting description of the construction and maintenance of this work, up to the time of its abandonment.

---

[1] The superstructure along the outer half of the breakwater has been entirely washed away.

[2] *Min. Proc. Inst. C.E.*, vol. xxxvii.

[3] "Harbours and Docks," Harcourt. Clarendon Press Series.

The difference in the effect produced by waves upon a composite breakwater having a long rubble slope carried up to or above the level of high water of spring tides, and one in which the level of the surface of the rubble mound is such as to admit of "mound-made" translatory waves reaching the superstructure, was very clearly exemplified at Holyhead during a storm which occurred on the west coast towards the end of the year 1889.

The mound of the Holyhead breakwater was carried up to the higher level (H. W. springs) almost throughout its entire length; but for a comparatively short distance, near the seaward end, it was not brought up much above the level of low water of spring tides, fears having been entertained that the wave action would cause the rubble to travel round the head into the harbour.

During the storm referred to, the structure was nowhere affected excepting where the mound was low. At that point, however, the waves struck the "bull-nose," or projecting string course, at the level of 19 feet 3 inches above high water, and displaced it, at the same time overturning the parapet which rested upon it.

The range of spring tides at Holyhead is the same as at Alderney, namely, 17 feet.

Crests on Waves, in the open ocean, are formed by the wind urging the top of the wave—which is its most exposed portion—forward at a greater speed than the body of the wave, and thus causing *that portion of the wave* to break by pushing it over.

A wave will sometimes carry its crest for a long distance, and in such a condition it is dangerous to vessels, especially those of small size. Such waves do not, however, disperse, and cannot therefore be viewed as "breakers" in the true sense of the term. This cresting or breaking of the tops of waves is most noticeable during the time that they are being raised by the wind, and before they attain a velocity commensurate with that of the wind.

A wave crests and breaks in a somewhat similar manner when crossing a sunken reef or shoal. In this case, however, instead of the crest being urged forward, the body of the wave is held back and caused to mount. The free and regular circulation of the particles being thus interrupted, the top, owing to its momentum, and to the fact that it is the part least affected by bottom friction, over-runs the other portion of the wave, and "breaks." So soon, however, as the shoal has been passed, the mass of the wave under-runs the broken crest, and the wave proceeds as one of reduced volume, the amount of reduction varying according to the depth of water over the shoal and the height of the wave traversing it.

Wind-crests and the irregularity which is often present in the run of waves during the height of a gale tend, in some degree, to aërate the waves. This may account for the well-known fact that more damage is often done to sea-works during the period in which a gale is subsiding than during its height. The waves appear to become more regular, and in a manner to steady themselves, as the force of the wind diminishes, and they are thus better able to throw their full weight against any opposing structure.

I am indebted for much of what follows respecting the velocity of waves, and indeed for a great deal of information on other points, to the admirable treatise (to which I have already referred) on "Tides and Waves," by Sir G. B. Airy.

Velocity of Waves.—When the length of a wave (crest to crest) is not greater than the depth of the water, the velocity of such wave depends (sensibly) only on its *length*, and is proportional to the square root of its length.

When the length of a wave is very much greater than the depth of the water, or, in other words, when the water is very shallow compared with the length of the wave, the velocity of such wave depends (sensibly) only on the *depth*, and is proportional to the square root of the depth. It is, in fact, the same as the velocity which a free body would acquire by falling from rest, under the action of gravity, through a height equal to half the depth of the water. The formula for accelerated motion is therefore applicable, viz.—

$$V = \sqrt{2gS} = 8{\cdot}02\sqrt{S}$$

V = Velocity of wave in feet per second.

g = Unit of force of gravity, or the velocity which a falling body attains, in vacuum, at the end of the first second = 32·17 feet per second.

S = Space in feet fallen through, or, in this case, half the depth of the water.

Long waves in deep water have therefore the greatest velocity, regardless of their height.

The above formulæ are not applicable to ground-swell waves, or to waves caused by earthquakes.

This, I think, is evident from the waves which were set up by the great eruption of Krakatoa (Straits of Sunda) in the year 1883. These waves were about 5 feet in height when they reached Algoa Bay,[1] South Africa. They were duly recorded by a graphic tide-gauge, which was fixed in water of 21 feet in depth, and freely exposed to the ocean. Their average velocity when passing this gauge was about 600 feet per second, and their average period was about 70 minutes.

The calculated velocity for a long wave in this depth of water would be only 26 feet per second.

The periods of these waves, although on an average about 70 minutes, were very irregular. The greatest recorded interval between crest and crest was 120 minutes, many had intervals of about 80 minutes, and the smallest for well-defined waves was about 45 minutes.

Owing to the great length of the waves as compared with their height, they were not discernible by the eye, but the effect was that of a series of high and low tides, with varying intervals as above stated. The water was smooth at the time, and the occurrence was extraordinary and perplexing. It is evident that such waves are altogether abnormal. Maury states that those caused by the earthquake of Simoda, in Japan, in the year 1854, had lengths of from 221 to 256 miles, crest to crest, and their velocities varied from 427 to 438 miles per hour.[2]

Such waves are sometimes spoken of as "free waves," a free wave being one which continues its course after the generating impulse or disturbance which produced it has ceased. Thus, waves produced by dropping a stone or other substance into water are free waves; so also are waves known as "ground-swell," which continue to roll on after the gale which produced them has ceased, until they finally die away, by reason of expansion and fluid friction.

A forced wave is one upon which the disturbing force continues to act; as, for example, the waves of the sea during a gale. These waves are urged onward by the wind acting upon their windward surfaces. So soon as they are relieved from such pressure they become free waves.

---

[1] Algoa Bay is about 4690 geographical miles distant from Krakatoa.

[2] "Physical Geography of the Sea," p. 4.

Ground-swell undulations are sometimes very long as compared with their height, and they "feel" the bottom at great depths. The mid-ocean storms by which these rollers are generated often do not blow home. To this class of waves the well-known rollers of the Cape of Good Hope belong.

The veering or backing of the wind, to the extent of a point or two during a storm, causes a "lumpy" sea; and a shift in the direction of the wind, to any considerable extent, tends to reduce the height of waves; therefore the duration of a storm, *steadily in any given direction,* is an important factor in the raising of a heavy sea.

In support of the foregoing, I refer the reader to the records of gales given on p. 37, *et seq.*

A self-recording tide-gauge, fully exposed to the open ocean, but so arranged as not to be affected by ordinary passing waves, will plot a continuous diagram of the tidal wave, which will often be found to have by no means so regular and flowing a line as might have been expected. On the calmest days, undulations of several inches in height, and having varying but usually very long periods, will be represented in the diagrams.

A careful study of these will show that the ocean is being traversed by several sets of undulations. At certain periods undulations larger than the others will be found, they being, doubtless, equal to the sum of the volumes of the waves, which at these periods coincide.

Such undulations as those to which I now refer are not discernible on the surface of the water, so that their existence would not be suspected but for the sensitive instruments by which they are recorded. These different series of undulations may either be travelling in the same direction with different periods, or in different directions with equal or unequal periods.

I quote the following from Reid's "Law of Storms," chap iv., respecting the direction of swell raised by storms.

> "Whilst sailing on the borders of the tropic in the Northern Atlantic, I have frequently watched the gradual change in the direction of the swell supposed to proceed from distant gales of wind, and it seemed to change in conformity to the usual progressive track of storms.
>
> "When living in the Bermuda Islands, I was frequently interested by observing the change of direction in the surf which beat against their shores. A coming storm would roll its undulations so as to

break upon the south and south-west side of these Atlantic islands, and as gales proceeded northward the sea was seen breaking on the northern reefs.

"I apprehend that the great undulations raised by the wind in revolving storms are raised along the radii of the whirlwind circle, and roll straight onwards in the direction of tangents to the circle of the whirlwind."

The foregoing record seems to be of special value on account of the observations having been made from an island so far removed from the mainland that the direction of the swell would not be influenced by it.

Height of Waves.—There seems to be a general tendency to over-estimate the height of waves, and statements on the subject, to which credence can scarcely be given, are frequently made.

It was stated by Lord Dunraven that breaking waves on the south-west coast of Ireland had been known to attain a height of 150 feet.[1]

Captain Sir E. Belcher, C.B., records having encountered waves 90 feet in height, trough to crest, while crossing the Gulf Stream in H.M.S. *Bellerophon,* during a voyage from Newfoundland to England.[2]

Waves are reported to have been often seen in the south bay of Peterhead, N.B., which obscured the Buchan-Ness lighthouse from the view of an observer stationed on the quay of the old harbour.[3] This, under the conditions which are specified, would have necessitated the waves being from 90 to 100 feet high, trough to crest; but there must have been a mistake in this instance, because the soundings along the line of sight are such that no waves approaching such a height could possibly exist.

It is probable that during storms the height of spray or broken water is often estimated, instead of that of the actual wave, and that the grandeur of the scene is conducive to exaggerated ideas being formed.

I believe it may be safely assumed that the greatest height of storm-waves, trough to crest, does not exceed 50 feet, excepting, perhaps, about the region of Cape Horn, where, from apparently well-authenticated records, their height sometimes seems to exceed 60 feet.

---

[1] Rankine, "Civil Engineering," p. 756.

[2] "Report of Select Committee on Breakwaters and Harbours, 1860," p. 54.

[3] "Report of Committee on Employment of Convicts, 1884," p. 49.

In the year 1883, Captain Molony, at that time first officer of the Union Royal Mail Steamship *Moor*, running between Southampton and the Cape of Good Hope, wrote to me, in reference to the highest waves he had ever witnessed, as follows:—

> "We fell in with the waves referred to in the middle of February, 1883, about 60 miles west-north-west of Cape Finisterre. They were so high that, when standing upon our bridge-rail, which is upwards of 31 feet from the water, and which would of course make the height of eye over 36 feet before lifting to them, they would appear at least 10 or 12 feet higher than where we stood, and thereby obscure the horizon completely until the ship lifted to them.
>
> "There are several people who will not believe this; but I assure you it is a fact. Captain —— (commanding the steamship *Moor*) and I have spoken about the height of these waves on several occasions, and we would not yield a single foot to any one. There had been incessant westerly gales for some time previous to our sailing, which would account for this mountainous sea."

Of the height of the waves in the Bay of Biscay during the storm which occurred in December, 1893, Admiral De Horsey wrote as follows:—

> "On Wednesday last (December 20) we experienced a gale the equal of which I have never seen. Between the squalls the sea rolled mountains high. Our forebridge (H.M.S. *Resolution*) is 37 feet from the water, and some distance from the bows. From that the approaching wall of water blocked out my view of the horizon. Forty feet is a low estimate of the height of these rollers."

These statements closely correspond with Captain Scoresby's observations in the Atlantic Ocean, the greatest height of waves which were there carefully observed by him having been 43 feet.

Airy states that he is inclined to think that in no circumstances does the height of an unbroken wave exceed 30 or 40 feet.

The late Mr. Thomas Stevenson, in his excellent work on harbours, referring to this subject, states that "the waves noticed by Scoresby in the Atlantic, which were 43 feet, may perhaps have nearly attained the maximum height for any gale, however great the depth, or however long the distance over which it acts." He also gives the following formula, based upon numerous actual observations, for calculating the height of waves during heavy gales.

Height of waves in feet = 1½ times square root of fetch in nautical miles.

This, of course, is on the assumption that the depth of water is sufficient for the full development of the waves, and that the storm is of sufficiently long duration to raise them to the maximum height of which the fetch will admit.

For short fetches, Mr. Stevenson considers the following formula more accurate:—

$$H = 1{\cdot}5\sqrt{D} + (2{\cdot}5 - \sqrt[4]{D})$$

H = height of waves in feet during strong gales.

D = fetch, or length of exposure, in nautical miles.

Mr. Hawksley has also constructed a formula for calculating the height of waves, which is likewise based upon numerous observations; but the results obtained by applying it vary to a very material extent from those which Mr. Stevenson's formula gives.

In view of the numerous conditions which affect the height of waves, it seems doubtful if it is possible to construct any reliable formula by which it can be calculated.

In estimating the possible height of waves, whether by the use of formulæ or otherwise, it should be remembered that, under conditions the most favourable to wave propagation and transmission, the height of waves (trough to crest) is limited by and does not exceed the depth of water which they are traversing, and, further, that the maximum height of waves (region of Cape Horn perhaps excepted) is generally admitted to be between 40 feet and 50 feet. Be this as it may, an engineer need not be very solicitous about waves over 40 feet in height, because, in designing a work to occupy a position where such waves could assail it, he would not be likely to err by making it too strong.

From a staging in Algoa Bay (Cape Colony) I have measured, with a sounding chain and weight, unbroken passing waves of 21 feet in height, trough to crest, in water of 23 feet in depth. These were set up by a gale having a wind velocity of about 60 miles per hour. The fetch was practically unlimited, being open to the Indian Ocean, and the depth of water gradually increased seaward at the rate of about 4 fathoms per mile. This was as high a sea as any that occurred during my residence at Port Elizabeth, which extended over a period of nine years; and some of the oldest inhabitants told me that the waves were as high on that occasion as any they remembered to have seen.

At another time, in the year 1883, I measured unbroken waves 13 feet in height, trough to crest, as they passed under the same staging during a south-east gale which had been blowing for about fifty consecutive hours, the maximum wind velocity being 68 miles per hour—equal to, say, 23 lbs., pressure per square foot—and the depth of water and length of fetch as before.

Again, during a south-east gale which quickly followed the foregoing, and which had been blowing for three days, the wind velocity at the time of observation being 58 miles per hour, I similarly measured unbroken passing waves having a height of only 10 feet. Their length, crest to crest, was 200 feet, and their velocity 20 feet per second. The depth of water was about 24 feet.

It will be observed that the greatest wind velocities recorded during these three gales were respectively 60, 68, and 58 miles per hour; whereas the greatest heights attained by the waves on the three occasions were respectively 21 feet, 13 feet, and 10 feet, fetch, depth of water, etc., being in all cases practically the same.

There can be little doubt that this apparent anomaly was due to either or both of the following causes, viz. a difference in the range of the respective gales, or a variation in the direction of their course—possibly far from land.

The wind velocities were automatically recorded by an excellent anemograph, so they may be considered reliable, at all events for purposes of comparison.

I have given the results of these three different sets of observations because I think they clearly show that, even in gales of considerable duration, a given fetch, wind velocity, and depth of water will not always produce waves of uniform height, such height depending greatly upon the varying conditions of the gales producing the waves, both as regards their extent and duration *in one direction.*

The direction of gales, without doubt, often varies considerably in a distance of 200 or 300 miles from the shore.

This is one more instance illustrating the necessity of extending the period over which observations are taken as much as possible, within reasonable limits, before placing reliance upon them. It is evident that deductions based upon the fact of a gale, with a velocity of 58 miles per hour, having produced waves of only 10 feet in height, under the conditions stated, would be most misleading.

In the Bay of Peterhead, during a storm of long continuance which occurred in the month of November, 1888, I noted, by means of lines of sight at known levels, waves of 26 feet in height (trough to crest), with occasional "lumps" considerably higher. These waves were 500 feet in length, and their period was from 12 to 12½ seconds, giving a velocity of 41 feet per second, or about 28 statute miles per hour. The depth of water where these waves were observed was from 7 to 8 fathoms, deepening seaward at the rate of about 12 fathoms per mile. The fetch on the line of the gale was about 450 miles, and the wind velocity was judged to be 70 miles per hour. These waves crested and broke when passing the 5½-fathom line.

It was stated, at the time of this gale, by residents in Peterhead, that these waves were not nearly so high as those which entered the bay during a previous storm, which occurred in the year 1873.

The maximum height of the waves (21 feet) recorded during the gale described on p. 37 seems to have been limited by the depth of water (23 feet), the fetch being unlimited, and the wind velocity sufficient to have raised waves of greater magnitude; whereas I think we should be right in assuming that the height of the waves referred to in Peterhead Bay was limited mainly by the force of the gale and the distance over which it acted, inasmuch as the depth of water was sufficient to have admitted waves of greater height.

Mr. Stevenson's formula, applied to this case, gives 32 feet as the possible maximum height of waves, and thus supports the statement, already mentioned, that waves of greater height than those observed by me had, on at least one previous occasion, been seen in Peterhead Bay.

Waves running into an inlet or bay with converging sides and a gradually shoaling bottom, have their energy compressed into a smaller body of water, thus giving them increased height, and adding to their translatory power.

Wick Bay, on the north-east coast of Scotland, is a good example of such a bay.

A similar effect may be produced by the convergence of submerged rocks, or contours. It is believed that the height of the waves at the Dhu Heartach Light, off the west coast of Argyle, is greatly increased by such a formation of the sea-bed.

Impact of Waves.—The intensity of the stroke of waves is due, in a great measure, to the non-elasticity of the water.

The difference between hydrostatic pressure and hydrodynamic force may be illustrated by taking a high-pressure water service as an example. So long as the water in the pipes is at rest, only the pressure proportionate to the head of water has to be considered; but set the column of water within the pipes in motion by opening a sluice-valve, and a new force at once comes into operation. If such force be suddenly arrested by the too rapid closing of the sluice, a burst pipe will probably be the result, unless, as is customary, a suitable relief-valve has been placed on the pressure side of the sluice. Hence, in a high-pressure water service, screw-down cocks take the place of plug taps, on account of the suddenness with which the latter close.

If such precautions are found to be necessary in arresting the progress of so comparatively insignificant a moving column of water as that above referred to, some idea may be formed of the resistance which must be offered in order to *suddenly* stop such moving columns of water as are represented by translatory storm-waves.

The dynamical effect of waves striking a plain surface is not easy to estimate. In the case of one non-elastic body striking another similar body the blow is infinite, and one or both of the bodies must be shattered.

The greater the elasticity of one or both of the bodies so coming into contact, the more is the effect of the blow reduced; hence the results obtained from dynamometers arranged with springs and plungers are liable to variation according to the strength and range of the springs used. For this reason it is probable they do not faithfully represent the force of a blow struck by a wave upon a non-elastic surface, such as that presented by the upright face of a breakwater or rock.

The error arising from this cause may be reduced, in some measure, by the wave remaining in contact with the surface struck for an appreciable time. I apprehend, however, that after the stroke has been delivered, only hydrostatic pressure, as distinguished from hydrodynamic force, is exerted.

A column of water having a velocity of 41 feet per second, as in the case of the storm waves referred to on p. 39, is such as would be produced by a 26-feet head of water. It would therefore exert a *pressure* of only 1622 lbs. per square foot; whereas the *dynamical force* of storm waves has been registered at as much as 6083 lbs., or nearly 3 tons per square foot.[1]

Examples of the effect and power of waves will be found in the chapter upon "Exposure," p. 73.

Wave-action on Beaches.—It is well known that off-shore winds cause beaches to heap up, while on-shore gales draw them down; or, as I have heard fishermen say, "the sand works through the wind."

It would, perhaps, be too much to say that this rule is applicable under all circumstances, but it will generally be found correct.

It has been observed that, under certain conditions, the period of waves may be taken as an indication of the action that is going on. Thus, for instance, seven or any less number of waves per minute would indicate erosive action, whereas nine or any greater number would indicate an accumulative action.[2]

Although, under the conditions existing where these observations were made, the period of the waves was doubtless a fairly reliable indication of the action that was going on, I think there are many cases where such a rule would not apply.

Sandy shores, exposed to the constant long roll from the ocean, will be found (at least, such is my experience) to alternately accumulate and be pulled down more in obedience to the direction of the wind than to the period of the waves, and I have noticed that some shingle beaches are affected in the same manner.

The reason why a change in the direction of the wind should so affect the action of waves upon a beach is not well understood.

I have on several occasions endeavoured to fathom the mystery by watching the motion of balls of burnt clay, which, owing to their form and comparatively small specific gravity, were easily moved by the waves; but, I must admit, the results of these observations were not such as to enable me to base any theory upon them.

---

[1] *Trans. Royal Society of Edinburgh*, vol. xvi.

[2] "Coode's Description of the Chesil Bank," *Min. Proc. Inst. C.E.*, vol. xii.

A paddle-steamship, going at full speed, and suddenly having her engines put at half-speed or dead slow, would, by her momentum, advance for some time at a speed that would cover a greater distance than that represented by the periphery of her wheels multiplied by the number of revolutions made by them. The wheels would, therefore, to a certain extent, be dragged through the water by the vessel's momentum, and, assuming that they touched the soft bottom, they would drag a portion of the material of which it was composed along with them, notwithstanding that they would be revolving in a direction which, under different circumstances, would have caused them to draw the material towards them and cast it out behind. I have often watched rollers coming in after a gale, the wind having suddenly chopped round and blowing strong off-shore at the time. These rollers appeared as in the following sketch, (Fig. 8), with their crests, so to speak, being dragged off by the opposing wind. It was impossible to say, from observation, how the motion of the revolving particles constituting such waves was being influenced, but might it not be that the period of their revolution was thrown out of beat or harmony with the speed of the wave, the off-shore wind acting as a brake, and the momentum of the waves, meanwhile, enabling them to maintain their form, notwithstanding that the motion of their particles was being thus disturbed? They would thus drag upon the bottom, like the floats of the paddle-wheels, and so set up an accumulative action.

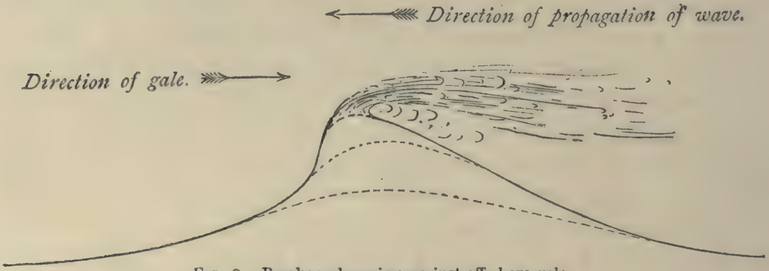


FIG. 8.—Breaker advancing against off-shore gale.

The opposing action of the off-shore gale would, of course, in time, altogether check and reverse the motion of the particles, and propagate waves in the opposite direction.

The composition of a beach, no doubt, affects the question to some extent. It seems obvious that where a beach is composed of open material, such as shingle, a large proportion of the run of the waves must be absorbed by filtration, so that stones being borne along or thrown forward by the waves are deposited as the water recedes, the volume, and consequently the power, of the drawback being greatly diminished. Possibly this may, in some measure, account for the slopes of shingle beaches, especially near the top, being so steep as they often are.

CHAPTER III.

TIDES.

Theory of tides—Spring tides—Neap tides—Tidal wave never perfectly formed—Priming and lagging of tides—Effect of variations in distance of sun and moon, also of declination—Diurnal and semi-diurnal tides—Equinoctial spring tides—Summer and winter tides—Progress of the tidal wave—Tidal range in Bay of Fundy, Bristol Channel, etc.—Tidal range in open ocean—Tides in Mediterranean Sea—Double tides—Tides at Batsham—Tidal "establishment"—Tidal harmonic analyzer—Mechanical prediction of tides—Harmonic analysis of tidal records—Effect of wind upon tides—Effect of atmospheric pressure upon tides—Effect of tidal range upon sea-works—Use of, and facilities afforded by, tidal range—"Bore."

ALMOST all works constructed in tidal seas are, in a greater or less degree, affected by the tides. The subject is, therefore, one which demands careful attention.

Newton, Laplace, Airy, and others, have done much to explain the observed phenomena of tides; but the difficulties—which it is needless to detail here—connected with a *complete* explanation of the subject are such that the conclusions—or at least some of them—which have been arrived at, are admitted to be more or less unsatisfactory, they having been based upon premises involving arbitrary conditions which do not exist in nature, but which it was, nevertheless, necessary to adopt, in order to bring the subject within manageable limits.

It is generally admitted that the admirable treatise by the late Astronomer Royal, Sir G. B. Airy, published in the "Encyclopædia Metropolitana," contains the most complete information on the subject of tides of any work extant; and the deductions drawn by him, from an examination of the several theories which have been propounded, and also from experiments which were conducted by Scott Russell, the Webers, and others, may be considered sufficiently accurate for all practical purposes.

In the present volume, a much more general description of the subject than is there given must suffice. I have, however, made free use of the learned astronomer's work, and will often refer to it in the following pages.

By the law of gravitation, which was discovered by Newton, bodies attract one another in *direct* proportion to their respective masses or weights, and *inversely* as the squares of the distances between them.[1] In accordance with this law, it is evident that our globe is being attracted in all directions by the various celestial bodies. In dealing with the subject of tides, it will however, only be necessary to consider the effect produced by the sun and moon; the influence exerted by the other stars and planets being insignificant and unworthy of notice by reason of their great distance from the earth, notwithstanding that in some instances their mass is very great.

Theory of the Tides.—The theory of the tides which is now almost universally accepted, is that known as the Newtonian or equilibrium theory. It is, however, based upon the hypothesis that our globe is a perfect sphere, enveloped entirely by water of uniform depth, and it can therefore only be received as approximately correct.

The sun and moon exert their attractive power with greatest effect upon that part of the water of the ocean which is immediately opposite to, and therefore nearest to them.

Thus the sun, by overcoming or reducing terrestrial gravity, raises the water into a heap on a line joining its centre with that of the earth, and the moon raises a similar but larger heap on a line joining its centre with that of the earth, the elevation of these respective heaps being proportionate to the relative effective powers of attraction of the sun and moon.[2]

---

[1] The truth of this law has been placed beyond question by the vast number of astronomical predictions based upon it, which have been fulfilled to the letter.

[2] Taking the mass of the moon and its distance from the earth as units of weight and distance respectively, the mass of the sun will be represented by, say, 26,000,000, and its distance by 391. The attractive power which the sun exercises upon the earth as a whole, as compared with that of the moon, is thus as $\frac{26,000,000}{391^2}$ to 1. In other words, the sun pulls at the earth with a force 170 times greater than that exerted by the moon.

The mean radius of the earth is 3956 miles, and the mean distance of the moon from the earth 237,600 miles. If, therefore, we take the earth's radius as unity, the distance of the moon from the centre of the earth will be represented by 60, from its near side by 59, and from its far side by 61.

The attractive forces exercised by the moon on the near and far sides of the earth are therefore as $\frac{1}{59^2}$ to $\frac{1}{61^2}$, the difference being 6·7 per cent. (say $\frac{1}{15}$).

By the same process, assuming the mean distance of the sun from the earth

UNIVERSITY OF TORONTO
DEPARTMENT [illegible]

The water on the opposite side of the earth, owing to its greater distance from the attracting bodies, is acted upon in a less degree than the great mass of the earth itself, and consequently "sags" or falls away from the earth, to an extent almost the same as that to which the water immediately under the sun and moon is raised.

The effect is therefore practically the same as if a force were drawing away the water from the earth on that side, and the general water-surface takes approximately the form of a prolate-spheroid, or that of a solid formed by revolving an ellipse about its longer axis. Inasmuch as the moon, as a tide-producer, is much more powerful than the sun, the tides are governed by her, and they follow her apparent passage round the earth, thus giving us two tides in the course of each lunar day.

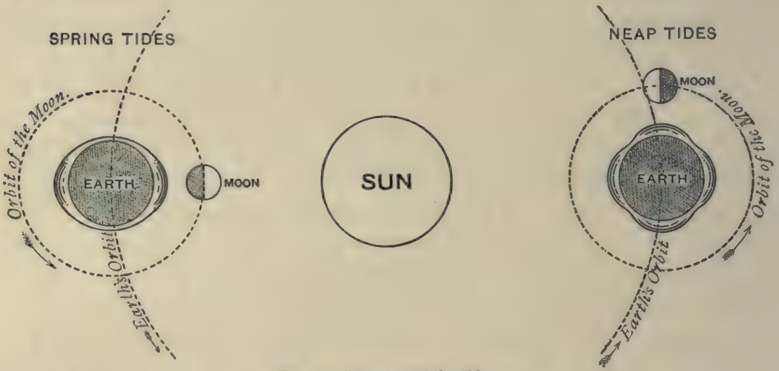


Fig. 9.—Diagram of the tides.

Spring Tides.—When the sun, moon, and earth are in one straight line—called the line of syzygies—which occurs twice in each lunar month, the sun and moon act in unison to raise the water on the two opposite sides of the earth, to an extent proportionate to the sum of their effective attractive powers, which, according to the laws of gravity, as already pointed out, are about as 1 to $2\frac{1}{3}$. Thus the highest, or what are known as "spring tides" are produced.

Neap Tides.—The moon, in her passage round the earth from

---

to be 93,000,000 miles, it may be shown that the difference between the sun's attractive force on the near and far sides of the earth is only $\frac{1}{5877}$ of its whole attraction.

Thus the proportion which the moon's *effective* attraction for tide-producing purposes bears to that of the sun is as $\frac{1}{15}$ to $\frac{170}{5877}$, or as 2·3 to 1.

west to east, advances eastward rather more than 13 degrees daily. During the same period the sun apparently advances somewhat less than one degree. The moon, therefore, increases her angular distance from the sun by rather more than 12 degrees daily, and consequently in somewhat less than 7½ days (7 days 9 hours 11 min. 1 sec.) after new or full moon she is at right angles to a line joining the sun and earth, or at her first or third quarter, as the case may be.[1] Her attractive power, at such times, raises the water on the sides of the earth in line with herself, and draws it away from the sides in line with the sun, while the sun is playing a similar part, though with less effect ($\frac{1}{2\cdot3}$ that of the moon), on a line at right angles to that through which the moon acts. In this way the high tide of the moon is made to coincide with the low tide of the sun, and *vice versâ;* the result being that the tides of the sun and moon tend to neutralize one another, and the water does not, therefore, rise so high or fall so low as at "springs."

The tides at this period are known as "neap tides," the range of which, as compared with spring tides, is about as 5 to 13.

When the sun and moon are on the same side of the earth, the upper tide of the sun coincides with the upper tide of the moon, and the under tide of the sun coincides with the under tide of the moon, their respective volumes being added.

When the sun and moon are on opposite sides of the earth, the upper tide of the one coincides with the under tide of the other, and the effect is practically the same.

The water-spheroids are but imperfectly formed, owing to the distribution of land, irregularity in the depth of the ocean, and the fact that the movements of the earth and moon do not give time for their proper formation.

With reference to the distribution of land, although the tidal wave is dealt with, theoretically, as though it revolved round and round the globe, the same wave cannot traverse the globe twice, because, with the exception of a comparatively narrow channel (about 500 miles) between Cape Horn and South Shetland or the land which it is believed stretches northward from the south pole, there is a practically continuous land barrier from pole to pole at about 70° west longitude. The effect of this barrier, in arresting the freest portion of the tidal wave in the Southern Ocean, is very apparent by the crowding together of the cotidal lines[1] in the hook which the east coast of Patagonia forms north of Cape Horn.

---

[1] The moon passes the meridian in periods of 24·814 hours, or 48 min. 50 sec. later every day.

"Priming" and "Lagging" of Tides.—At new and full moon, the respective high and low waters of the lunar and solar tides being superposed, the observed tide is, as will have been gathered, a compound one.

When these tides do not exactly coincide, the maximum elevation and depression of the compound tide will lie somewhere between those of the tides of which it is composed, but they will be closer to those of the lunar tide, by reason of its greater magnitude.

If, therefore, about the time of new or full moon, the sun passes the meridian before the moon, the crest of the solar wave is slightly in advance of that of the lunar or main wave, and the tide is "primed," or accelerated. If, on the other hand, the sun passes the meridian after the moon, the crest of the solar wave lags behind that of the lunar wave, and the tide is said to "lag," or be retarded. This explains why the periods between successive observed tides are so irregular as they are, notwithstanding that the lunar and solar tides, individually, recur at equal intervals of time.

The extent to which this retardation and acceleration takes place does not exceed one hour, and it is greatest about 4½ days before and after spring tides.

Tides affected by Variations in Distance of the Sun, Moon, and Earth from each other; also by Declination.—Since the earth and the moon revolve in elliptical orbits, their respective distances from the sun, and from each other are constantly changing; and inasmuch as the power of attraction which bodies exert upon one another varies, as already stated, inversely as the squares of the distances between them, it follows that these variations must be reflected in the tides.

The effects thus produced are modified by the declination of the sun and moon, and by the varying power of the sun's attraction upon the moon. In short, every variation in the relative positions of the sun, moon, and earth, whether recurring at daily, monthly, or annual periods, or extending over a series of years, produces a corresponding effect upon the tides; and it is in this way that the differences which we find in morning and evening tides, in ordinary and equinoctial tides, and in summer and winter tides, are accounted for.

---

[1] These are contour lines of high water plotted at intervals of one hour, thus showing the progress of the tidal wave over the ocean.

Diurnal and Semi-diurnal Tides.—The difference in the range of diurnal and semi-diurnal tides, which is very apparent in many localities, is attributable to variation in the attractive power of the sun and moon on opposite sides of the earth, resulting from declination.

Speaking generally, during one half of the year the highest tides occur in the morning, and during the other half of the year in the evening. This difference, in some cases, amounts to several feet. Indeed, in the Gulf of Mexico, and in some positions near Behring Strait, the difference of morning and evening tides is so great that, in certain parts of the lunation, there appears to be only one tide in the day.

At Singapore this inequality amounts to as much as 6 feet, and around the coast of Australia it is also very marked.

This difference between morning and evening tides is, however, greatly affected by local circumstances, and seems to follow no general law.

Equinoctial Spring Tides.—When the sun is vertical over the equator, as is the case at the vernal and autumnal equinoxes in March and September, its attractive power upon the water immediately beneath it is then greatest; and when the lunar tides, at new and full moon, coincide with the solar tides about this time, which, owing to the small declination of the moon, they do more closely than at other times, abnormally high and low tides occur. These are known as "equinoctial spring tides."

Difference in Range of Summer and Winter Tides.—The earth, revolving in her elliptical orbit, is nearer to the sun at mid-winter, and further away from it at mid-summer than at any other periods of the year. Hence the attractive power which the sun exercises upon the earth is greater in winter than in summer, and the range of the tides is correspondingly affected, that of the winter tides being increased, while that of the summer tides is diminished. The declination of the sun, which reaches its maximum on the 21st of June and 21st of December respectively, however, considerably modifies the sun's influence on the tides at these periods; and it is in consequence of this that the range of mid-winter tides is not so great as that of those occurring at the equinoxes, when the sun, although slightly more distant from the earth, is vertical over the equator, in which position its effect upon the tides is greatest.

At mid-winter, the increase of tidal range due to the nearness of the sun to the earth, is reduced by the sun's declination; but at mid-summer both the sun's distance and declination tend to reduce the tides, which are thus the worst in the year.

Progress of the Tidal Wave.—In consequence of the free motion of the tidal wave being obstructed by the irregular contour and distribution of land, and also by the retarding effect upon its progress produced by decrease of depth and other disturbing causes, the time of high water at any given place will not be found to coincide with the time of the moon's passage of the meridian, unless, indeed, the retardation has been such as to cause the crest of some previous tidal wave to arrive at that time.

A chart with cotidal lines marked thereon, shows at a glance to how great an extent the tidal wave is thus interfered with, and how it is made to wheel and expand in all directions in order to fill the various more or less land-locked seas, gulfs, and inlets, so that in many places the tides on any given day are really those due to the position of the sun and moon, it may be, two or three days previous.

Inasmuch as the tidal wave traverses the globe once in about every 24 hours 49 min., its velocity at the equator, where unimpeded, is about 1000 miles per hour. In the preceding chapter it was stated that the velocity of long waves depends on the depth of the water which they traverse, and that, as they advance into shoaler water, their length, and consequently their velocity, decreases, while their height increases. This applies equally to the tidal wave; and we find that as it advances into shallow seas and estuaries its velocity is diminished and its height increased, to the extent which local physical conditions demand.

The tidal wave in its normal state is one of oscillation. When, however, its progress is interfered with—as, for instance, when it has to find its way through shallow and contracted channels, or by circuitous routes, into seas or estuaries—its character is changed, and where the obstruction is great, it seems to lose its wavelike character, and to assume that of a stream, which, where steep gradients occur owing to difference in water-level, often runs with great velocity until equilibrium is re-established. The rapid tidal currents through the Pentland Frith, and through many of the narrow channels to be found about the Hebrides and elsewhere, are produced in this manner.

The velocity at which these tidal currents run is, however, quite distinct from that of the tidal undulation. Thus in the North Sea, along the east coast of Scotland, the velocity of the tidal stream is from 2 to 3 knots per hour, while that of the tidal undulation is upwards of 50 knots.

When tidal water passes into converging river channels, or estuaries, its momentum causes it to heap up, and abnormal range of tide is the result. A shoaling, or gradual decrease in the depth of the water, produces a similar effect, the velocity of the tidal wave being reduced, and its height increased.

The gradual convergence of the shores, and shoaling of the water in the Bay of Fundy, give rise to the exceptional and notorious range of tide there, which is said to amount to fully 60 feet at the head of the bay.

When it is considered that the range of a spring tide at the mouth of the bay is only about 8 feet, such an extraordinary increase is certainly remarkable.

This bay, which lies between New Brunswick and Nova Scotia, is roughly 180 miles in length. Its width at the entrance—which approximates in form to a bell-mouth—is about 60 miles, converging gradually to about 20 miles near the head of the bay, where it bifurcates into two comparatively narrow and shoal arms or inlets.

We find the tidal range affected in precisely the same manner in all estuaries and bays where the tide is free to enter, only in varying degree according to their several physical conditions. The estuary of the Bristol Channel may be cited as a good example. There the range of tide at the entrance is about 18 feet; but, owing to the funnel-shaped contraction of the channel, and gradual shoaling of the water, it is made to rise to about 27 feet at Swansea, 37 feet at Cardiff, and 50 feet at Chepstow.

At Avranches, where the range of tide at springs is about 39 feet, the cause, though somewhat similar, is not quite the same. A large portion of the tidal wave, in passing up the English Channel, is stopped by the French coast (Cape La Hogue) projecting so far across the English Channel, opposite to St. Alban's

Head, as to abruptly reduce its width by about 40 per cent. The tidal water is thus diverted into the angle or "bight" on the French coast, at the apex of which Avranches is situated; and the converging coasts impound this water, which is thus made to heap up to the extent named.

The effect of this sudden narrowing of the channel, and impounding of the water, is clearly shown by comparing the tidal range at Dartmouth, the islands of Guernsey (St. Peter's Port), Jersey (St. Heliers), and at Avranches.

If upon a base-line the respective positions of Dartmouth, Guernsey, Jersey, and Avranches be marked, and the tidal ranges at these several places plotted—viz. Dartmouth 14¼ feet, Guernsey 26 feet, Jersey 31 feet, and Avranches 39 feet—a line joining these respective heights will be found to give an almost uniform gradient of 3 inches per mile. The periods of high water at these several places occur within about 20 minutes of each other, and are therefore nearly synchronous.

Normal Rise of Tides.—The observed or compound tides rise and fall respectively twice in each lunar day, one being the positive or upper tide, and the other the negative or under tide.

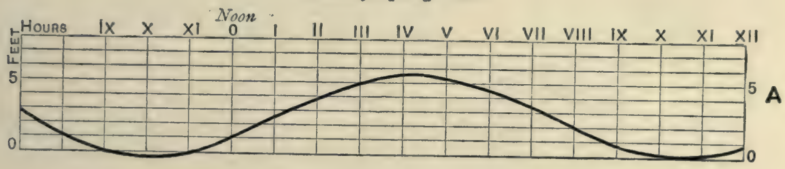
The normal rise of tides in the open ocean, at the equator, where it is obviously greatest, has been variously calculated; but it is generally assumed that the rise of spring tides is from 2 feet to 3 feet, and that of neap tides from 10 inches to 15 inches. Airy calculated ("Tides and Waves," p. 355) that, in the open ocean, the height of the solar tidal wave above the normal water-level would be 0·61 foot, and that of the lunar wave 1·34 foot; thus giving a height of $0·61 + 1·34 = 1·95$ foot at spring tides, and $1·34 - 0·61 = 0·73$ foot at neap tides. Newton, on the other hand, calculated that spring tides would rise about 6⅔ feet, and neap-tides 2⅔ feet. Observations made on islands in the open ocean seem, however, to endorse the accuracy of Airy's calculation.

In the Mediterranean Sea—except at the extreme western end, where the tides are influenced by those from the Atlantic—the range of tide is very small, by reason of the tidal wave being throttled at the Straits of Gibraltar.

The tidal range, due to the direct tide-producing action of the sun and moon upon the waters of small seas, bays, and estuaries, is so small as to be altogether unworthy of notice. Even in the Mediterranean it is insignificant, only amounting to two or three inches; nevertheless, this scarcely perceptible range is increased to 3 or 4 feet at the head of the Adriatic Sea, probably from the same cause as that referred to in connection with the great range in the Bristol Channel and elsewhere. In view, however, of the general shape of the Adriatic, one would scarcely have expected to find the tidal range there affected to such an extent.

Double Tides.—What is known as a double tide, or double high water, is usually caused by portions of the tidal wave reaching a given locality by different routes, their respective times of arrival depending upon the distance traversed, difference in velocity—which is generally occasioned by variation in depth—or by other physical conditions.

Ordinary Spring Tide.



Ordinary Neap Tide.

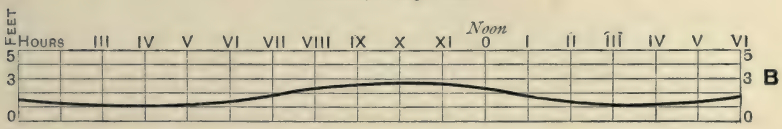
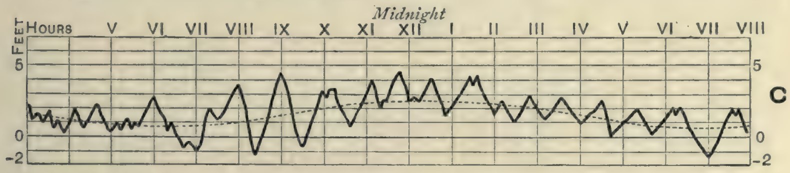


Diagram showing commencement of long series of Earthquake Waves caused by volcanic eruption at the Straits of Sunda, as recorded by the tide-gauge at Port Elizabeth. August 27, and following days (1883).



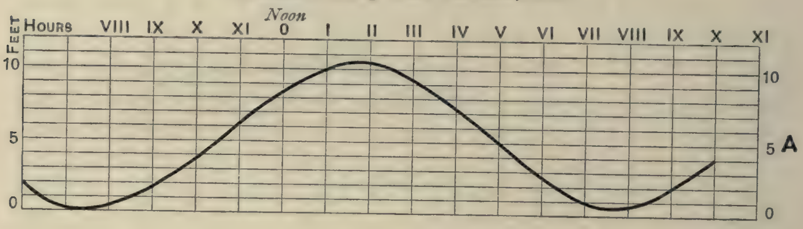
The dotted line shows the normal curve of tide. Abnormal waves did not disappear from the diagrams for seven days.

FIG. 10.—Tidal curves, Port Elizabeth (South Africa).

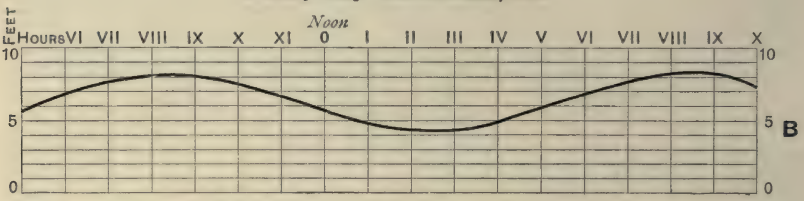
A well-known example of this—one of many—is to be found at Southampton, where the western channel of the Solent affords a deeper and more direct course to the town than the eastern arm. The portion of the tidal wave which passes up this channel therefore reaches Southampton earlier than that which passes up the eastern channel, and so an apparently double tide is formed, as indicated by the diagram (Fig. 11, C) on next page.

In parts of the North Sea, tidal irregularities are caused by the waters which pass through the Straits of Dover meeting those from the northward, which have been delayed in their passage along the western coasts of Ireland and Scotland, as will be described later on (Chap. IV.).

Ordinary Spring Tide, Peterhead, N.B.



Ordinary Neap Tide, Peterhead, N.B.



Curve[1] of Spring Tide at Southampton, showing double high water.

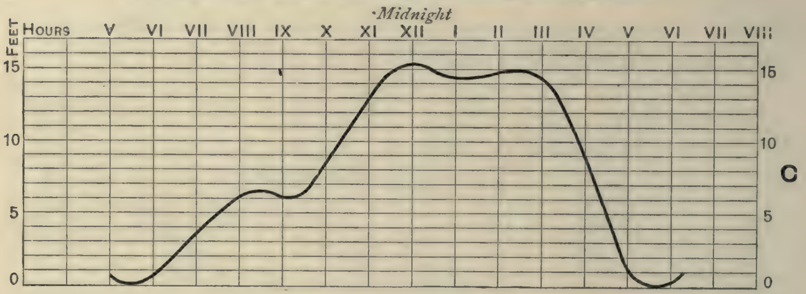


FIG. 11.—Tidal curves.

At Batsham, in Tonquin, one portion of the tidal wave, which comes from the Indian Ocean, obliterates another portion from the China Sea, so that scarcely any tide is perceptible. This is due to the interval between the arrival of these undulations being about equal to the period between high and low water, so that the crest of one and the hollow of the other arrive simultaneously, and neutralize each other.

---

[1] Enlarged from diagram in Sir G. B. Airy's "Tides and Waves" ("Encyclopædia Metropolitana").

The tidal range at many points around our own coasts, as well as in other parts of the world, is much affected in a similar manner, although not to so great an extent.

Tidal Establishment.—On the days of new and full moon, the moon passes the meridian at 12 o'clock (nearly), and the time of high water at any port on such days is called the "establishment" of that port.

The *approximate* time of high water on any other day may be found by adding the "establishment" to the time of the moon's passage over the meridian on that day.

In order to accurately determine the establishment of any port—an important point, both in regard to sea-works and navigation—a series of careful tidal observations must be taken. With the view of eliminating error, or equalizing irregularities, these should be plotted in diagram form (see Figs. 10, 11). Ready-made diagrams, obtained by means of self-recording tide-gauges, are, however, much to be preferred.

The time of high water on the days following new moon, full moon, first quarter, and third quarter, may be pretty accurately ascertained by adding the "establishment" to the time of the moon's passage over the meridian; but from new moon to first quarter, and from full moon to third quarter, high water occurs somewhat earlier than would be indicated by the above process; and from first quarter to full moon, and from third quarter to new moon, it occurs later.

Owing to the earth not being truly spherical, to the irregular distribution of land and water, and to the great variations in the depth of the latter, the calculation of the time of high water for any port is one of some difficulty, requiring the use of the higher mathematics. Sir William Thomson (now Lord Kelvin) has, however, invented two machines, one of which he terms a tidal harmonic analyzer, and the other a tide-predictor, their object being—to use his own words—"to substitute brass for brain in the great mechanical labour of calculating the elementary constituents of the whole tidal rise and fall."

These machines perform their work in the most perfect manner. All that is required is to furnish the operator with a set of tidal observations, or the curves drawn by a self-recording tide-gauge, for any particular port; care being taken that the observations or diagrams thus furnished shall, so far as possible, be normal—that is to say, unaffected by winds or abnormal barometric changes; otherwise, errors may be introduced and repeated, which the instrument cannot eliminate.

From these tidal curves, an analysis having been made by the first-named machine, the tide-predictor can graphically predict, for the same port, for future years, not merely the times of high and low water, but the positions of the water-level at any instant of any day of the year, assuming the tides to be normal.

A full description of these machines is given in vol. lxv. of the *Minutes of the Proceedings of the Institution of Civil Engineers.*

The harmonic analysis of tidal records, by means of the former of these machines, was inaugurated by a committee of the British Association in 1868, and since that time the subject has received much attention.

Papers upon it, by Major Baird, R.E., Mr. G. H. Darwin, F.R.S., and others, have from time to time been published in the *Proceedings of the Royal Society.* These tend to show what an extremely complex curve that of the tidal wave is; nevertheless, its main features remain as already described, and it is not necessary, for the purposes of this work, to enter more fully into that branch of the subject.

Effect of Wind.—The tides are often much affected by wind. A strong wind, counter to the tide, or to an ocean current, may, by checking its run, cause it to bank up the water in bays or inlets along the coast. This is very marked during a strong westerly gale against the Agulhas Current, along the south coast of Africa. In Algoa Bay such a gale is off-shore, and it might with some reason be expected to lower the tides by blowing the water out of the bay. In taking a wider view, however, it becomes evident that this westerly wind checks the Agulhas Current, which flows across the mouth of the bay in a westerly direction, and causes the water to bank up, which it often does to the extent of from 12 to 18 inches.

On the north-east coast of Scotland, where the flood tide runs in a southerly direction, the tides are raised by a westerly or south-westerly wind, inasmuch as such winds accelerate the tidal flow along the west coast, where the direction of the flood tide is northerly, and thus increase the volume of water entering the North Sea through the Pentland Firth and other northern channels. A northerly or north-easterly wind checks the flow of the tide along the west coast, and thus lowers the tide in the northern compartment of the North Sea. In the southern compartment, and along the west coast of Holland, the tides are raised, or banked up, by northerly and north-westerly winds.

The normal rise of spring tides on the west coast of Holland is about 5 feet 9 inches, but strong north-west gales sometimes cause a rise of from 9 to 10 feet.

In the English Channel south-westerly winds raise the water-level, whereas north-easterly winds depress it.

The Black Sea, being practically tideless, offers facilities for noting the effect of various winds upon the water-level; and it is found that along the west shore—say the coast of Bulgaria—during a strong off-shore or westerly wind, the surface of the water is lowered to the extent of 18 inches, whereas during a strong easterly wind—which crosses a reach of water nearly 600 miles in length—the surface is raised about two feet above the mean water-level; thus giving a total range of 3 feet 6 inches, due entirely to the action of the wind.

At Venice, a strong south-east gale raises the tides to the extent of about 18 inches, and a strong northerly gale lowers them to a corresponding extent.

What has been said on this point will suffice to show how important it is to ascertain the effect of gales upon the water-level, because the height of quays, stagings, or even of breakwaters themselves, may be greatly affected by it, and the injurious effect of waves be much increased.

Effect of Atmospheric Pressure.—With regard to the effect of atmospheric pressure on the tides, it may be remarked that the weight of the atmosphere at the earth's surface is represented by a pressure of about 15 lbs. per square inch. This is equivalent to nearly $8\frac{3}{4}$ tons per square yard, or to a layer of iron a yard and a half thick, spread evenly over the whole surface of the globe.

Seeing that the entire surface of the ocean is thus loaded, it is evident that if a portion of the load be removed locally, the water will rise in proportion to the amount of relief so given, and conversely, if the load be increased the water-surface will be depressed.

The barometers in common use record atmospheric pressure by comparing it with the height of a column of mercury which it will balance. Hence, if we say the barometer stands at 30·20, we mean that the pressure of the atmosphere is such that it will just balance a column of mercury 30·20 inches in height.

The weight of mercury is about 13¼ times that of sea-water; therefore a local rise or fall of the barometer amounting to, say, one inch, would represent a depression or elevation, as the case might be, of the surface of the ocean at that place to the extent of about 13¼ inches.

The effect of atmospheric pressure in various places is, however, not uniform, being affected by local conditions.

On this point Airy writes—[1]

> "We cannot do better than refer the reader to Mr. Lubbock's paper, *Phil. Trans.*, 1837, p. 97, etc. It appears there that in a set of observations considered by Mr. Lubbock, the unexplained fluctuations of the tide correspond precisely to those of the barometer; and Mr. Lubbock has laid it down as a rule that a rise of 1 inch in the barometer causes a depression in the height of high water amounting to 7 inches at London, and to 11 inches at Liverpool. Mr. Bunt also, in the "Eleventh Report of the British Association," p. 31, has discussed with great skill the effect of the barometer on the tides at Bristol, and has shown that a rise of 1 inch of barometer produces a depression of 13·4 inches."

A very little reflection will show to what a large extent the proportions, and consequently the cost, of sea-works are affected by range of tide.

Let us assume a vertical breakwater to be situated in a tideless sea, where the depth of water is 20 feet, the width of such breakwater being 30 feet, and its height 10 feet above the waterline. Such a breakwater would contain 100 cubic yards of material per lineal yard.

A similarly proportioned structure in the same depth at low water, but where the rise of tide was 10 feet, would contain nearly 178 cubic yards of material per yard forward.

The quantity of material in a pell-mell mound breakwater, constructed of concrete blocks, and having a top width of, say, 30 feet, with a slope on the seaward side of 1½ to 1, and on the harbour side of 1 to 1, would, under similar conditions, be increased by 58 per cent.

---

[1] "Tides and Waves," p. 390.

The cost of the rubble-mound type of breakwater is, however, affected by range of tide more than any other. This will be apparent on reference to the accompanying diagram. On comparing the sectional areas of the several mounds there indicated with that of mound A—which represents the section that would be required in a tideless sea—it will be seen that even so moderate a rise of tide as 7 feet, in the case of a breakwater constructed in water having a depth of 40 feet at low water, would entail an addition of 66 per cent. to the quantity of material employed. A range of 15 feet would increase the quantity 2½-fold, and nearly four times as much material would be required in constructing such a breakwater where the range of tide was 25 feet.

In tideless seas, the area of breakwater face exposed to the wave-stroke is constant, and the work may be designed accordingly; but in the case of a structure situated where a range of tide exists, the additional area of face brought under the wave-stroke necessitates, so to speak, a corresponding extension of the armour.

The cost of building work within the tidal range is usually much in excess of that incurred in building above high-water mark, seeing that the workmen employed upon such work are unable to work steadily at it, and additional sea-risk is incurred, which

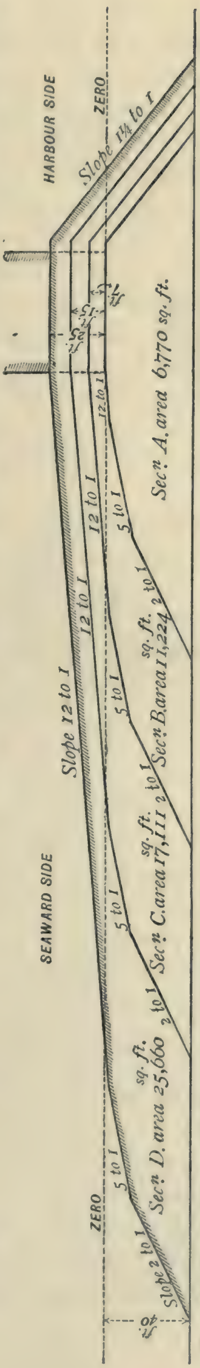

HARBOUR SIDE
ZERO
Slope 1¼ to 1
15 ft
25 ft
7 ft
12 to 1
5 to 1
Secⁿ. A. area 6,770 sq. ft.
2 to 1
Secⁿ. B. area 11,224 sq. ft.
Slope 12 to 1
Secⁿ. C. area 17,111 sq. ft.
Secⁿ. D. area 25,660 sq. ft.
SEAWARD SIDE
ZERO
Slope 2 to 1
40 ft

Fig. 12.—Diagram illustrating the extent to which the quantity of material in rubble mound breakwaters is affected by range of tide. The slopes indicated are those which the rubble mound of the Holyhead breakwater has now assumed.

Section A represents a mound such as would be required in a tideless sea, having a depth of 40 feet.
" B " " " with a 7-feet range of tide.
" C " " " " 15-feet "
" D " " " " 25-feet "
The exposure is assumed to be the same in all cases.

necessitates extra good work, and the adoption of precautionary measures to enable it, while "green," to withstand the wash of the sea.

On the other hand, work within the tidal range may be executed without the aid of divers; so that, in some cases, the facilities which range of tide affords for executing work below the *mean sea-level*—if that datum be assumed instead of low water—may, in a measure, compensate for the extra cost which it involves above that level.

Notwithstanding what has been stated in reference to the prejudicial effect of tidal range under certain conditions, particularly in regard to the construction of breakwaters, it is scarcely necessary to say that the importance of tides is such that they constitute *the* power upon which, when properly directed, depends the very existence of the great majority of navigable river-channels.

Numerous creeks and small bays are also, by tidal range, rendered available as harbours for the smaller class of shipping, more particularly for that class which is engaged in the fishings. Sometimes such bays or creeks are naturally protected by outlying rocks, and in other cases shelter may be afforded, at a moderate cost, by taking advantage of natural facilities.

Fishing-boats and other small vessels enter these harbours at high water, or whenever there is sufficient water to admit of their doing so; and as the tide recedes they settle down upon, let us hope, an even, soft bottom, and lie secure, unless, as sometimes happens, they are ruthlessly disturbed by the "run" caused by storm-waves entering the harbour.

The great drawback to tidal harbours is that they are not available for purposes of refuge at all times of the tide—a fact which often entails very serious loss of life and property.

Judging, however, from their number, and from the additional harbours of this class which have been constructed of late years, and are still being constructed, it is evident that the shelter and accommodation which they afford, imperfect as it may be, is appreciated.

Many docks, including graving docks, are entirely dependent upon tidal range for their working, their sills being often laid at or above the level of low water; and but for tidal range, those useful structures called "gridirons," whereon vessels are so often conveniently cleaned and repaired, would have no existence.

Apart from the fact of tidal water being instrumental in maintaining the depth in river-channels, only vessels of the smallest class could reach such ports as London, Hull, Bristol, Cardiff, etc., if tidal range did not exist. It is, further, eminently useful from a sanitary point of view. These considerations, however, apply chiefly to river-works; and, excepting in the case of small breakwaters or piers constructed above low-water mark, range of tide is decidedly prejudicial to breakwater construction.

Where the tidal range is considerable, advantage is sometimes taken of it to lift and float large blocks of concrete into position, they having been previously constructed upon a suitable platform. This system was adopted and, I believe, initiated by Mr. B. B. Stoney, in works which he carried out in the River Liffey. Large blocks (about 70 tons in weight) were also transported and placed in position in this manner, under Sir John Coode's direction, in the Jersey harbour works.

There are many interesting phenomena connected with the tides in rivers and estuaries, but a consideration of them here would carry us into a field of inquiry which lies outside the limits of this work.[1] I will, however, before closing this chapter, say a few words in reference to the curious phenomenon which is known by the name of "bore."

When an estuary contracts shoreward, and when its depth decreases so as to form flat low-lying foreshores, if the rise of tide is considerable and rapid, the tidal wave advances over this flat foreshore in the form of a "breaker," or "bore." This is due to the tidal water rushing on with great rapidity, and the wave —or it may be only its wings—being raised and made to break as it traverses the shore on either side of the channel.

Bores may vary in height from only a few inches to many feet, according to the conditions under which they are formed. In the Severn they attain a height of from 5 to 6 feet at spring tides, the wave being of less height in mid-stream, where it does not break. In the Amazon their height is said to be more than double this. Bores also occur in the Hoogley, Orinoco, Solway Frith (above Silloth), Morecambe Bay, the Seine, the Gulf of Fundy, and other places.

In a bore, as in a wave breaking upon the sea-shore, the velocity of the wave and of the water which transmits it are nearly equal, the wave being pre-eminently one of translation.

---

[1] The subject has been fully treated in "Tidal Rivers," Wheeler. Longmans.

Commander W. U. Moore, R.N., thus describes the bore of the Tsien-tang-Kiang:

"While the flood tide is travelling across the sands, the water is rising steadily at the end of the navigable portion of the Hang-chau gulf; and by the time the two branches of the bore join there is a difference of level of 19 feet, at springs, between the water on the outside of the bar and that in the mouth of the river, a distance, in a direct line, of about 20 miles. Accordingly, the flood enters the river down a gradient of 1 foot in a mile with great force, and is assisted by the transmitted pressure of the advancing tidal wave in the estuary. The speed, as measured by the officers of H.M.S. *Rambler*, is 12·7 knots, or 14·6 statute miles, an hour. The bore has a breadth of 9 cables, or 1800 yards, and its front is a gleaming white cascade of bubbling foam, 8 to 12 feet high, pounding on itself and the river in front of it at an angle of from 40° to 70°, the steepest and highest portion being over the deepest part of the river, where the outgoing stream has the greatest velocity.

"The noise is not the least impressive feature of the phenomenon. On a calm, still night it can be distinctly heard, when 14 or 15 miles distant, an hour and twenty minutes before arriving. The noise increases very gradually, until it passes the observer on the bank of the river with a roar but little inferior to that of the rapids below Niagara.

"The bore maintains its breadth, height, speed, and regular appearance for 12 or 15 miles above the mouth of the Tsien-tang-Kiang."[1]

[1] *Min. Proc. Inst. C.E.*, vol. xcix.

CHAPTER IV.

CURRENTS.

Origin of ocean currents—Evaporation and precipitation—Water-circulation in Mediterranean and similar seas—Effect of wind on currents—Temporary currents caused by wind—Currents running counter to prevailing winds—Tidal currents—"races" or "roosts"—Velocity of littoral currents increased by breakwaters projected across them—Effect of currents upon height of waves—Strong currents out of harbours objectionable.

It is believed that the heat of the sun's rays and the rotation of the earth upon its axis—whether acting directly upon the waters of the ocean or through the medium of the winds—are the two principal forces which produce and give direction to ocean currents. These must not, however, be taken to include tidal currents, which owe their origin to the tidal wave being impeded in its progress, as will be more fully described later on (p. 69).

Whatever causes an inequality in the level of the surface of the ocean, or in the density or specific gravity of its waters, disturbs equilibrium, and a current, which may be regarded as an effort of nature to restore the lost balance, is at once set up. The subject of ocean currents is, however, as yet far from being perfectly understood.

Water, in common with other substances, expands with heat, and in so doing its specific gravity is diminished. If, therefore, any portion of the ocean be heated more than the water which surrounds it, its bulk will be increased, and, as a natural consequence, its surface will be raised. This will cause the warm-water to flow off, in order to find its normal level; but the warm-water column, being thus relieved of weight, will continue to rise, on account of the lower and heavier stratum of cold water forcing itself underneath it. This cold water will, in

UNIVERSITY OF TORONTO
DEPARTMENT OF CIVIL ENGINEERING
[illegible] Structural

its turn, be warmed as it approaches the surface, and the warm off-flowing stream will in this way be maintained.

It is evident that, so long as the flow of warm water from the surface continues, the supply of cold water must be kept up. Whence, then, comes this supply ?

From investigations which were carried on during the voyage of H.M.S. *Challenger*,[1] it would appear that the temperature of the ocean is in general, though not always, highest at the surface, and that it decreases rapidly for the first hundred fathoms, then less rapidly down to 500 or 600 fathoms, after which it decreases very slowly, but generally progressively, to the bottom.

These differences in temperature are undoubtedly connected with the great ocean currents, which form a general system of circulation, the movement of the warm surface water from the tropics towards the poles necessitating a compensating return current, or drift, from the poles towards the equator.

It is worthy of note that this underlying mass of cold water, just referred to, which at its lower depths has a temperature scarcely, if at all, above the freezing-point of fresh water, should, immediately under the equator and in other hot regions where the surface water has a temperature of somewhere about 70° Fahr., approach nearer to the surface than elsewhere. The fact that it does so seems to support the view, already expressed, that the comparatively light column of warm water is raised by the denser cold water forcing itself underneath it, whereby the warmer water is made to flow off in the form of surface currents.

The mean normal temperature of the superficial portion of the earth's crust, and therefore of the bed of the sea, may be taken at not less than 45° or 46° Fahr. It is clear, therefore, that this mass of cold water, which must be undergoing constant renewal, owing to the flowing-off and evaporation of the surface water, cannot derive its low temperature from equatorial regions, but must come from a place where the conditions are such as to impart to it a freezing temperature.

Sir Wyville Thomson states[2] that he was able to trace a band of water of similar low temperature, continuously from the equator to the Antarctic Sea. There seems, therefore, to be no room for doubt that this cold water is supplied from the region of the poles, and that the warmer water makes its way thence, to be cooled down ready for its return journey.

---

[1] "Voyage of the *Challenger*," Thomson, vol. ii.

[2] Ibid, vol. ii. p. 302.

Sir Wyville Thomson believes that the cold water comes mainly from the Southern or Antarctic Sea, and assigns as a reason the fact that the several series of temperature soundings, which were taken in the North Atlantic, seemed to show that the lower stratum of water at or near the equator was colder than any between it and the Arctic Sea.

The heat of the sun's rays not only induces this circulation of surface and under-currents by its direct action, but it also plays a similar part through the medium of evaporation and precipitation.

The amount of evaporation from the surface of the ocean within the tropics has been estimated, from experiments made at St. Helena by Dr. Halley, to be about 8600 cubic yards per square statute mile per diem.

We will assume, for the purpose of obtaining some idea of the volume of water thus raised, that the *average* rate of evaporation from the whole water-surface of the globe is equal to one-half of this. We shall thus have 146,000,000 square statute miles—the computed approximate[1] water-area of the globe—multiplied by $\frac{8600}{2}$ cubic yards per square mile per diem, which gives about 115 cubic miles, or say 42,000 cubic miles per annum, as the quantity of water taken from the ocean by evaporation. This corresponds to an evaporation of only 18 inches per annum, which is a small allowance.

Maury estimates the evaporation from the ocean at a very much higher figure.

In the Persian Gulf, it is said to be upwards of 15 feet.

However, whatever the correct amount may be, the principle involved, viz. that ocean currents are affected by evaporation, remains the same.

The capacity of the North Sea basin, assuming an average depth of 35 fathoms (which is approximately correct), is roughly 6300 cubic miles.

A mass of water nearly seven times greater than that which the North Sea contains, is therefore—at my low estimate—abstracted from the ocean annually by evaporation, and is transported hither and thither, in the form of vapour, by the winds.

---

[1] The water-area of the globe is variously estimated, the differences in the several calculations being mainly due to the manner in which the unexplored regions of the poles are dealt with.

It is, moreover, all returned to the ocean again, either directly in the form of rain or by rivers, after they have collected it from their catchment areas, thus doubling the effect.

It is obvious that so large a volume of water as this cannot be abstracted from the ocean and returned to it again, in the course of a year, without the circulation of its waters being, in a material degree, affected by it.

Respecting this, Sir Wyville Thomson states—

> "My general views with regard to ocean-circulation remain unaltered. I think, however, that we have now good reason to believe that the indraught of water at a low temperature into the Atlantic and Pacific—gulfs as we may almost call them—from the Southern Sea, is to a great extent due to an excess of precipitation over evaporation in the 'water-hemisphere,' and a corresponding excess of evaporation over precipitation in the 'land-hemisphere;' that, in fact, a part of the circuit of general ocean-circulation passes through the atmosphere."[1]

Evaporation affects the motion of water in another way.

When it takes place from salt water, the water which remains is salter, and therefore heavier, than it was before. Thus, though raising the temperature of salt-water reduces its specific gravity, evaporation tends to increase it. When, therefore, salt water is being heated, two processes are in operation, tending to counteract each other.

The surface water of the ocean, as it becomes salter by evaporation, is prone to sink. Its subsidence is, however, impeded by its relatively high temperature and by the manner in which the waves stir up the water to considerable depths and cause its particles to mingle.

During the voyage of the *Challenger* the question of the specific gravity of ocean water was very fully investigated. Numerous samples of surface water and of water from various depths and localities were obtained, and their specific gravities carefully ascertained and compared, due allowance being made for differences in temperature. From these tests it was found that, usually, the specific gravity of the surface water was the highest. It would, therefore, appear that in the open ocean the

[1] "Voyage of the *Challenger*."

currents carry off the warm surface water before it has time to acquire enough additional density, by evaporation, to outweigh, or even balance, the reduction in its specific gravity resulting from increase of temperature.

In such seas, however, as the Mediterranean and Red Sea, no circulation corresponding to that of ocean currents exists. The surface water is therefore not carried off, as in the open ocean, but it subsides when its salinity reaches a point which renders flotation no longer possible. Hence the salinity, and therefore specific gravity of the waters, increases with depth, being much greater at the bottom than at the surface.

The quantity of water taken from the surface of the Mediterranean by evaporation considerably exceeds that poured into it by rivers and rainfall combined, the deficiency being made up by a constant indraught from the Atlantic.

The amount of salt thus carried into the Mediterranean is very great, and is the means provided by Nature of setting up a circulation, without which, there can be little doubt, the waters of that sea would soon become like those of the Dead Sea. This salt, by descending, as before described, so increases the density of the water in the lower compartment of the sea that it enables, or indeed compels, it to force its way out against the lighter water of the Atlantic as an under-current, just in the same manner as so much quicksilver would do.

The waters of the Mediterranean and similar seas are thus made to circulate in quite a different manner to those of the ocean, notwithstanding that in each case the heat of the sun's rays is the prime mover.

We have now to consider the effect of wind upon ocean currents.

Winds, especially if blowing steadily in one direction for a considerable time, will set up surface currents; and *constant* winds, like the "Trades," undoubtedly influence ocean currents to a very great extent.

It seems pretty certain that the great equatorial westerly going current is much accelerated, if not chiefly caused, by the trade winds.

After leaving the region of the "Trades," this current very soon comes within the influence of the prevailing south-west winds. Its course is diverted by the eastern cape of Brazil (Cape San Roque), by which it is split into two streams of about equal magnitude. One of these is turned south-westward into the South Atlantic, while the other passes on to the West Indies and Gulf of Mexico, whence it emerges, through the Strait of Florida, as the Gulf Stream, and assumes a north-easterly direction. It pursues this course towards the North Pole, by way of the British Isles and the northern coast of Norway, doubtless as a return current to compensate the loss caused by the outflow, both as surface and under currents, of cold water from the pole to the equatorial regions.

It is worthy of note that the Equatorial Current, including its continuation the Gulf Stream, alters its course in about the same latitude and in the same direction as the prevailing winds; and, further, that the tracks of nearly all the memorable storms recorded by Reid in his work on the "Law of Storms and Variable Winds," coincide in a remarkable manner with the course of the Equatorial Current and Gulf Stream. With few exceptions, the direction taken by these storms appears to have been from about east-south-east until between the twenty-fifth and thirtieth parallels of north latitude, when they gradually assumed a more northerly direction, and, on arriving at about 30° N. lat., they began to trend away to the eastward, following very nearly the course of the Gulf Stream, as before stated.

It is well known, or at all events pretty generally believed, that aërial currents and ocean currents act and react upon each other; and I am disposed to think that the heated waters of the Gulf Stream cause an upcast aërial current along its course, tending to draw to it any storm that may chance to come within its influence.

In some localities, where winds blow with great regularity from particular quarters, temporary surface currents are set up by them. These are very liable to be mistaken for constant ocean currents if not observed for a sufficiently long period, and serious mistakes in the design of harbour works may thus be made.

That wind cannot be looked upon as the only, or even principal, current producing power, seems to be evinced by the fact that currents often flow against prevailing winds. For instance, the Agulhas current flows west against strong prevalent westerly winds, and the south-going cold surface current out of Baffin's Bay runs counter to the Gulf Stream and also to prevailing winds; indeed, it is common to find adjacent currents running in opposite directions. The great south equatorial drift current across the Pacific Ocean, with its counter current of about equal magnitude running parallel to it, may be cited as an example of this.

The currents which, in general, affect sea-works most are those which owe their origin to the tides.

The tidal wave does not produce currents unless it is interfered with, either by reduction in the depth of the water which it traverses, whereby it is changed into a wave of translation, or by the configuration and irregular distribution of land, or by both.

During flood tide there is usually a slight set towards the shore. It is, however, variable in direction. There is also a corresponding current or drift from the shore during the ebb tide. This arises from the action of the shoaling bottom upon the tidal wave, whereby it is made to wheel shoreward in consequence of its flank being held back by the friction of the shore. The wave is thus made to approach to parallelism with the coast.

On looking at a terrestrial globe, it will be seen at a glance how greatly the progress of the tidal wave is obstructed in all directions, and how, in consequence, tidal currents are set up.

Thus, to take a well-known example, the tidal compartment of the North Sea is partially filled and emptied through the narrow Straits of Dover. The process is, however, so slow, owing to the throttling of the tidal waters, that by far the greater portion of the tidal water in the North Sea has to be supplied from the northern end of it. In order that this may be accomplished, the tidal wave has to run northward along the west coasts of Ireland and Scotland, until, arriving at the Pentland Frith, it pours its waters through it, and through the channels of the Orkney Islands, at a great velocity, in its endeavour to equalize the respective water-levels of the Atlantic Ocean and the North Sea. The current or "race" thus caused through the Pentland Frith runs at times with a velocity of from 10 to 12 miles per hour, that through the Straits of Dover having a velocity, off the South Foreland, of about 3½ miles per hour.

Numerous examples of strong tidal currents, known as "races" or "roosts," may be found, especially amongst the islands on the west coast of Scotland.

One very noticeable instance of such a "race" with which I am familiar, is that at Kyle Rhea, between the Isle of Skye and the mainland. This channel (Sleat Sound) is trumpet-shaped, having a width at its southern entrance of about 5 miles, which, in a distance of 20 miles, contracts to less than half a mile at the Kyle Rhea ferry. Through this narrow channel the tidal waters rush with great velocity, in consequence of the Isle of Skye blocking up the channel between the mainland and the Western Hebrides to the extent of about 70 per cent.

The Sound of Jura contracts in a somewhat similar manner, causing a rapid race through its narrow northern channels.

In some rivers, or tidal estuaries, the configuration of the coast, coupled with a shoaling bottom, occasions a great range of tide, and the rush of water into the tidal compartment is often so great as to cause what is known as a "bore" (see p. 61).

Another cause of acceleration of the tidal currents may be here referred to, namely, that resulting from capes or headlands ponding back the water.

At such points the main body of water to seaward is, by its inertia, slow to give way or accommodate itself to these irregularities of coast-line, the result being that the passage or transfer of the inshore water from one side of the promontory to the other is obstructed. A "head," or difference in level, is thus produced on the up-stream side, resulting in a current which often attains a considerable velocity past the salient points.

In designing harbours this fact should not be lost sight of, since, in projecting long breakwaters into the sea to form a harbour, the tidal current running past the entrance may be so increased in velocity as to render it difficult for ships to take the harbour at certain times of the tide. An example of this may be found at the harbour of Ymuiden, on the west coast of Holland. The piers forming this harbour were projected into the North Sea for a distance of nearly a mile. Before they were built, the velocity of the flood current at spring tides along that part of the coast was from 2 to 2½ knots per hour, according to the direction and strength of the wind. As the piers advanced, the velocity of the current past their seaward ends steadily increased; and by the time they were completed the current past the entrance, during flood tide of springs, attained the inconvenient velocity of from 3 to 4 knots per hour. The speed of the current past the end of Dover pier was similarly increased as the structure advanced; indeed, it is not possible to project a close pier far into the sea without thus increasing the velocity of the littoral currents.

Pier-heads are very liable to be undermined or eroded by such currents, and it is often necessary to make special provision to guard against injury from this cause.

Currents will generally be found to run in a pretty direct course along a coast from headland to headland, those within such lines being often irregular, and partaking more or less of the nature of eddies.

A good deal of misconception exists about littoral currents, and they are not sufficiently distinguished from the run, or set along a shore, resulting from wave action, or from the temporary currents set up by wind. There is no doubt that imaginary littoral currents are very often credited with the transport of material along a shore, the movement of which is almost wholly attributable to wave action.

I do not wish it to be understood that those currents, where they exist, do not, under certain conditions, play an important part in the transport of material along a coast; but, excepting in cases where their velocity is considerable, it will be found that they play an insignificant part as compared with wave action, which I believe to be the chief agent at work in the movement of beach drift.

The foregoing remarks do not refer to the flood and ebb currents running into and out from the tidal compartments of rivers and estuaries.

There is scarcely any point in connection with sea-works which requires more careful attention than that of littoral drift and the forces by which it is regulated.

When strong currents are opposed by wind waves, the latter are increased in height, and often break and cause a dangerous sea. On the other hand, a current flowing in the same direction as the waves will tend to run them down, as will also a *strong* current running parallel to the waves. I was told, when at Scrabster, that the rapid current through the Pentland Frith shelters the roadstead there to some extent from northerly swell, excepting, of course, at slack water.

Captain William Campbell gave corroborative evidence on this point before the Royal Commission on Harbours of Refuge in

1858; and he went on to say that the tide had the same effect at Wick and "in all places."[1]

Sir James Dombrain—Inspector of Coastguard Service in Ireland—referring to Portrush, says, "The tides are so very rapid outside in the channel, that they keep down the sea whichever way they may be running."[2]

At Peterhead, N.B., where very high seas are at times experienced, the tidal currents run close past the heads of the south bay, and at spring tides they attain a velocity of about 3 knots per hour. Their direction corresponds very nearly with that of the troughs and crests of the waves during south-easterly gales. On several occasions, during such gales, I have endeavoured to find out what effect, if any, these currents have upon the height of the waves entering the bay, and, with this object in view, I have carefully observed the waves both at slack water and during the strength of the tide; in no instance, however, have I been able to detect any change, either in the height or character of the waves, which could be attributed to this cause. I therefore conclude that the shelter afforded by currents is a question of degree, which depends upon their velocity and direction in relation to the height and direction of the waves, the effect of a 3-knot current upon waves of from 15 to 20 feet in height, and running parallel to them, being inappreciable.

Tidal currents, judiciously directed by means of piers or training banks, constitute the chief force by which the depth at the entrances of most river or estuary harbours is maintained or increased.

In deciding the width of entrance for any harbour, it should be borne in mind that a strong current out of a harbour is objectionable, inasmuch as it is an obstacle to sailing vessels entering; and, when opposed by storm waves, a dangerous, short, breaking sea is likely to be set up.

[1] "Report of Royal Commission on Harbours of Refuge, 1859," vol. ii. p. 4.

[2] "Minutes of Evidence, Select Committee on Harbours of Refuge, 1858," p. 125.

CHAPTER V.

FETCH, EXPOSURE, AND WAVE-POWER.

Definition of "Fetch"—Fetch alone no indication of exposure—Wheeling of waves—Direction of waves affected by contours of sea-bed—Exposure of sites affected by shift of wind and by scour during gales—Glacial action mistaken for wave-power—Movement of earth's crust in relation to apparent effects of wave-power—Raised beaches—Ruins of temple of Jupiter Serapis—Effect of waves on coast near Wick; also at Holburn Head, Caithness—Effect of falling water—Evidences of wave-power in Zetland—Wave-power as displayed at Ymuiden, Kurrachee, Wick, Alderney, Scilly Isles, Wolf Rock lighthouse, etc.,—Mud as an indication of exposure—General remarks on exposure of sites.

Fetch and Exposure.—The distance over which waves may be driven by the wind to any particular point, is called the "fetch" to which such a point is exposed. Thus we say that a harbour is exposed, between certain limits, to a fetch of so many miles; by which is meant the distance, within such limits, to the opposite or windward shore, or to barriers, such as rocks or shoals, capable of stopping or interrupting the free run of the waves. In other words, "fetch" means the distance in any direction which can be *freely* traversed by undulations in the course of their development.

It is obvious that fetch, in itself, cannot be taken as the measure of the exposure of any site.

It may happen that gales never blow on the line of longest fetch, whereas heavy rollers may wheel round a point or headland which might have been expected to afford shelter. Moreover, gales and storms have bounds which vary in different localities, and which practically limit the effective length of fetch.

The harbour at Kurrachee is open to a fetch of 500 miles, and the depth of water is such as to admit of heavy waves being formed. Storms at Kurrachee are, however, unknown; and the largest waves, which are brought up by the south-west monsoon, do not exceed 15 feet in height, trough to crest.[1]

Similarly, at Colombo, notwithstanding that the site of the harbour is fully exposed, Mr. Kyle states that the greatest height of waves observed by him during the construction of the breakwater there was 12 feet in the offing, and 15 feet just outside the breakwater.[2]

It is thus evident that no general rule can be laid down for calculating the height of waves from the length of fetch and depth of water alone.

Points to be considered in judging of the height of waves likely to assail a sea-work have already been treated of in Chapter II.

In observing the direction taken by heavy waves—a very important point in laying out sea-works—it should be borne in mind that the shape of the contours of the sea-bed often varies very much at different levels, and that waves have a tendency to accommodate themselves to, or be guided by, the direction of such contours.

Thus, unless it is known that the formation of the sea-bed is such as not to influence the direction of the general run of the waves, it cannot, with safety, be assumed that waves of, say, 20 feet in height will advance in the same direction as waves whose height is only 10 feet, notwithstanding that the direction of the gale generating them may be precisely the same in each case.

Submerged gorges or converging sunken rocks, even at considerable depths, cause waves to heap up and assail, with increased force, any portion of a work up to which they may lead. Such a form of bottom is not uncommon, and it may always be regarded as an adverse feature. It is, therefore, of importance that a careful study be made of the contours of the sea-bed immediately in front of, and to some distance seaward, of a proposed work, more especially if such be situated on a rocky coast.

It often happens that a change of wind into a quarter from which the exposure is small will increase the sea in a bay or harbour, by causing the waves to wheel in the manner before referred to.

---

[1] *Min. Proc. Inst. C.E.*, vol. xliii.

[2] Ibid., vol. lxxxvii. p. 90.

For instance, the worst sea that is experienced at the harbour of Holyhead is caused by a north-west gale veering to north.

Similarly at Scrabster, on the north coast of Scotland, which lies under the shelter of Holburn Head, a north-west or north-north-west gale veering to the north or east of north causes the waves to wheel round the headland, and sends the heaviest sea into the bay. Again at Alderney, the worst seas are caused by south-westerly gales veering to north of west. At Algoa Bay (Cape Colony), very heavy rollers wheel round Cape Recife. These are caused by south-west gales, which, unless a comprehensive view of the district were taken, would be looked upon as blowing off shore. These rollers are sometimes so heavy that they prove more trying to the sea-works at Port Elizabeth than higher waves set up by gales blowing directly into the bay.

Were it necessary, numerous other examples might be given to illustrate this wheeling of waves; but those already cited will no doubt be considered sufficient.

In connection with depth of water, as affecting exposure, I may here mention a condition which is liable to be overlooked.

In judging of exposure from a chart or plan giving soundings, it is essential that the nature of the sea-bed, and its liability to scour or not, be ascertained, because the depth of water in front of some sea-works is often much increased by scour during the early stages of a gale. Heavier waves are thus enabled to advance further and further inshore during the continuance of the gale, and to throw their full weight against any opposing work. At Port Elizabeth I have often noticed such a deepening take place to the extent of 5 or 6 feet in a single tide along the front of the sea-wall there; and on the coast of Holland, in the neighbourhood of Ymuiden harbour, the water frequently deepens to the extent of fully 10 feet during the early part of a gale. When it is remembered that every extra foot in depth may mean an additional foot in height to the waves assailing a work, the significance of this scouring action will be appreciated.

Wave-Power.—On many coasts there are such astounding exhibitions of the apparently herculean power of waves, that we are led to consider whether the waves may not have been aided in the part they played by some power or circumstance of which we are not now cognizant, but which may have rendered the display of such seemingly prodigious force unnecessary in bringing about results such as those to which I now refer.

On the shores of the Bay of Peterhead, at about half-tide level, there are[1] some huge, erratic, water-worn granite boulders, which are not of the characteristic rock of the neighbourhood. The largest of these weighs at least 90 tons. These have been pointed out to me on more than one occasion as evidence of the force of the waves, which must have transported them from nobody knows where, and deposited them where they now lie. Doubtless, at first sight such an impression might easily be formed; but, as a matter of fact, these huge boulders were transported by glacial action, and the only part which the waves have played in placing them where they now lie has been that of washing away the clay from underneath and around them. In the cuttings of a railway which was formed through this boulder clay, similar boulders were met with at various levels; and many may also be seen protruding from the clay along the coast, some of which are scored by grooves, evidently caused by glacial action.

My own impression is that much may be accounted for and many apparent difficulties solved by taking into consideration the movement of the earth's crust (gradual or otherwise), which we know is going on in many parts of the globe at the present time, and to which, in past ages, we attribute many of the mighty changes which a study of geology reveals.

I had occasion, in constructing the railway before referred to, from the south bay of Peterhead to the admiralty quarries at Stirling Hill, to run a spoil bank of boulder clay into the sea. The action of the waves very soon washed down portions of this clay, and, removing the more solvent portions, formed a beach of boulders, gravel, and sand. The waves sorted these materials, and arranged them generally in alternating layers.

Throughout the cuttings along this railway, beaches, similar in every detail to the one so formed, occurred at various levels. One was cut through at the level of 50 feet above low water; another one of large extent at the level of 64 feet; and others at different levels up to about 175 feet above sea-level.

There is not the slightest doubt, in my mind, that these now-raised beaches which contain marine shells were, during successive periods, at the sea-level—and, in fact, formed the ordinary sea-beach, the levels at which they now lie being the result of gradual upheavals of the land, extending possibly throughout long ages.

---

[1] Some of these have been recently broken up and removed.

It is well known that at the present time parts of Norway and Sweden are being raised at the appreciable rate of something like 4 feet in a century, and that there are raised beaches, similar to those I have just described, existing at elevations of from 400 to 500 feet above the sea, and some miles inshore.

Lapland and Japan are also being slowly raised, whereas the west coast of Greenland has, for the last 400 years, been sinking at the rate of several feet in a century.

In the island of Jura, on the west coast of Scotland, there are six or seven lines of beaches, the lowest of which is on a level with high water, and the highest about 40 feet above it; indeed, the presence of similar raised beaches and ancient sea-cliffs, now inshore and high above the sea-level, furnishes strong proof that much of Scotland has been raised to a considerable extent within (geologically speaking) very recent times.

On the sea-coast at Pozzuoli, near Naples, may be seen the ruins of the celebrated temple built by the Romans in honour of Jupiter Serapis. Since that time the ground upon which it stands has been lowered and again raised to the extent of fully 20 feet, the most remarkable feature in connection with this movement being that it has been so gradual and even as not to overturn or disturb three columns which remain standing upright, notwithstanding that they are 41 feet in height and barely 5 feet in diameter at the base.

The evidence of this movement is, however, undeniable.

A belt, measuring about 8 feet in width, around each column has been perforated by the pholas; while, strange to say, from the lower margin of this belt to the base of the columns, a distance of 11 feet, the stone has not been attacked at all. This has been accounted for by assuming that the lower portion of the columns was embedded in mud, and so protected.

The work of the pholas can only have been performed under water. It therefore follows that the columns must have been immersed up to the level of the top of the perforated belts, or to a depth of at least 19 feet, and that they have been subsequently elevated to such an extent that the perforated belts may now be seen many feet above the water-level.[1]

As an example of a still more recent raising of land, I may cite that which took place in the north island of New Zealand, at the time of the earthquake in the year 1855. The surface of the ground at this place was raised to a maximum extent of 9 feet, and so remained.

---

[1] "Temple of Serapis," Babbage.

This change of level extended for a distance of 23 miles, in which length it gradually died out, and gave place to a depression.

It is needless here to multiply instances of such changes having taken place, those already mentioned being sufficient for my purpose, which is to show that the presence of large detached masses of rock or accumulations of boulders or blocks of rock, even at considerable heights above the sea-level, must not, without due investigation and clear proof as to the time when they were deposited, be taken as evidence of the force of the sea-waves at the present time, and, under existing conditions, at the places where they are found.

The cliffs along the coast south-westward from Wick Bay are vertical, and are composed of compact black schistose rock of the Devonian period. The beds are horizontal, or nearly so, and the layers of rock vary in thickness from a few inches to several feet.

On approaching the "Auld Man o' Wick" from the northward, the height of the cliff above sea-level is from 70 to 80 feet, and along this portion of the coast there is a remarkable display of the power of waves.

Fig. 13 is from a sketch which I made in the summer of 1889, upon the spot, from actual measurements. The heap of stones at B forms an almost continuous bank along the coast for a considerable distance. In many places, the blocks of stone of which this bank is composed—many, or indeed the majority, of which weigh several tons—have been lifted over ledges 7 feet in height, and driven uphill for a distance of fully 100 feet from the edge of the cliff.

A 15-ton block, as it now lies on its upward journey, is represented in the sketch.

There can be no doubt that at least some, if not all, of the stones forming this bank have been quarried, by wave-action, from the ledge A, because several may now be seen lying slued round from the sites which, prior to disturbance, they evidently occupied, their corners being crushed and broken by pivoting upon other portions of the rock, which are also crushed, and with which, in some instances, the stones are still in contact, clearly indicating the force which must have been exerted in moving them.

I measured one of these stones, which had been thus displaced, lying near the edge of the cliff, and found it to be 12 feet × 12 feet × 4 feet, representing a weight of at least 40 tons.

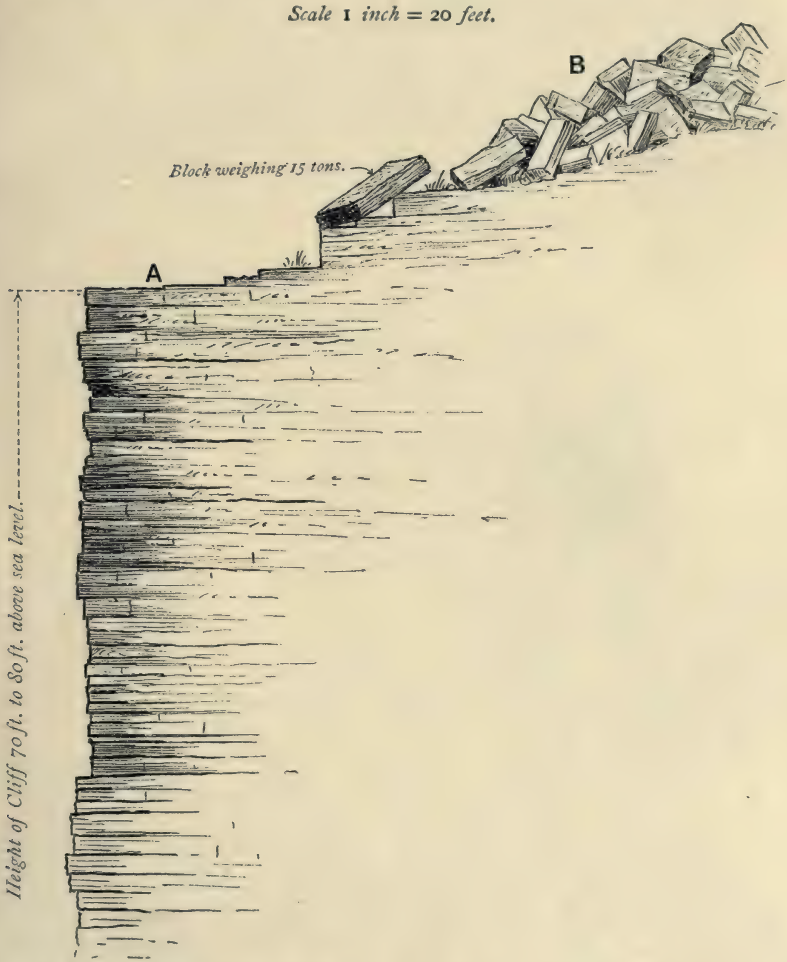

Scale 1 inch = 20 feet.
B
Block weighing 15 tons.
A
Height of Cliff 70 ft. to 80 ft. above sea level.

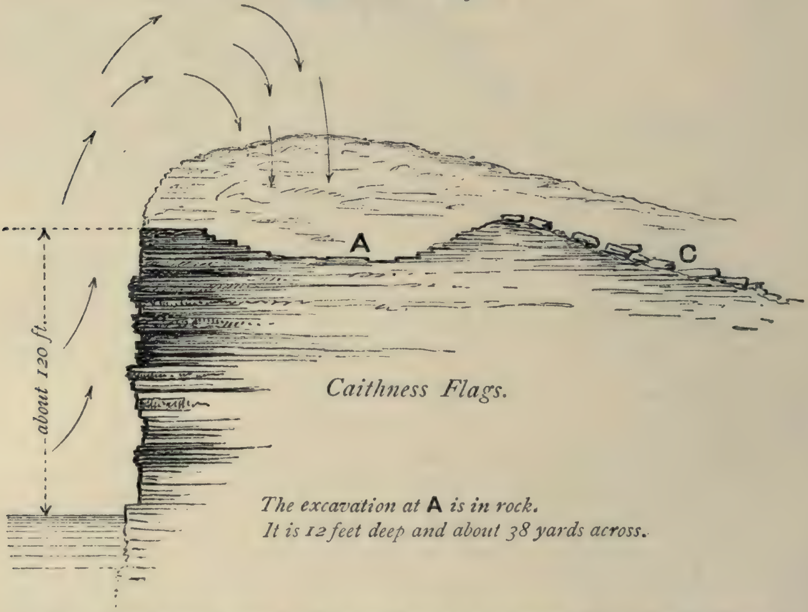
FIG. 13.—Sketch illustrating effect of waves on coast south-westward from Wick Bay.

All of these stones have lichens growing upon them, and grasses and sea-pinks are growing amongst them. It is therefore evident that they have not been recently disturbed; and, in view of the great weight of many of them, and their height above the sea, I cannot but think they must have been displaced and arranged as they now lie at a time when they were nearer to the sea-level than they are at present, the land having been subsequently raised.

Be this as it may, instances of what the sea can do, and is doing every winter, around the northern coasts of Scotland are not wanting.

Figs. 14 and 15 are from sketches which I made at Holburn Head, near Scrabster, on the north coast of Caithness.

Scale 1 *inch* = 80 *feet.*



The excavation at A *is in rock.*
It is 12 feet deep and about 38 yards across.

Fig. 14.—Sketch showing effect of falling water thrown up by storms at Holburn Head, Caithness.

A more instructive example than that which nature affords —as illustrated by Fig. 14—of the effect of falling water upon the roadway of a breakwater could scarcely be found. It was largely due to this action of the waves that the breakwaters at Alderney and Wick were laid in ruins, and it has been the frequent cause of serious damage elsewhere.

I was informed by the lighthouse-keeper at Scrabster, and by others, that scarcely a winter passes without the occurrence of one or more storms of such violence as to throw enormous masses of "green water" high above the cliffs, which, falling as at A, Fig. 14, excavate the rock, and, rushing down the slope C like a torrent, fall into the sea on the other side of the headland.

In reference to the effect of falling water, I ask the reader to note that a velocity of 41 feet per second, being that of the storm-waves referred to on pp. 39 and 41, is that attained by a free body falling through a distance of 26 feet.

It is no uncommon occurrence for storm-waves, striking a vertical breakwater face, to throw heavy masses of water to a height of at least 100 feet—often very much higher.

Such water in its descent, on reaching the roadway of the breakwater upon which it falls, will have attained a velocity of about 80 feet per second, or nearly double the velocity and four times the force of the water striking the face of the breakwater. Although the volume of the water thus falling is less than that of the wave, it is, nevertheless, often very great, and clearly points to the necessity of providing ample strength and close, well-made joints in the roadway of a breakwater occupying an exposed position.

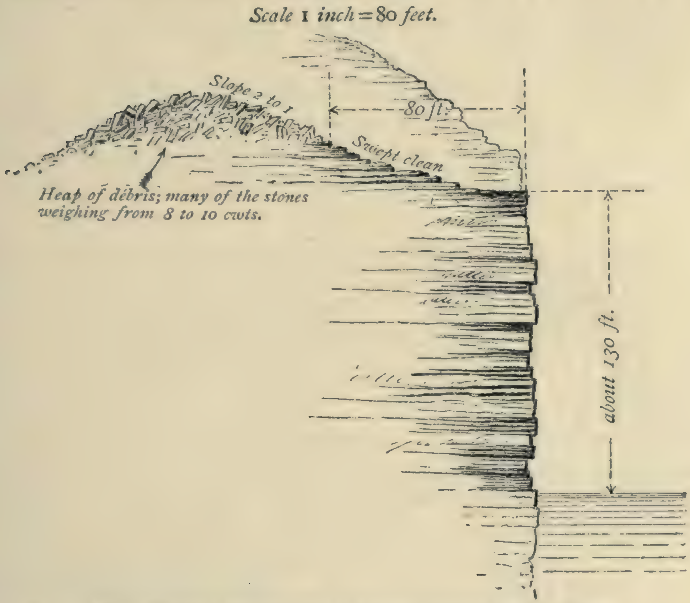

Scale 1 *inch* = 80 *feet.*
Slope 2 to 1
80 ft.
Swept clean
Heap of débris; many of the stones weighing from 8 to 10 cwts.
about 130 ft.

FIG. 15.—Sketch showing effect of waves at Holburn Head, Caithness.

In view of the foregoing, there would seem to be little cause for wonder that so many breakwaters have suffered damage through their roadways being ploughed out, these being too often constructed, it may be, with only a thin skin of concrete, or a foot or couple of feet of pitching, laid with open joints upon a hearting of loose rubble.

Fig. 15, p. 81, represents an action, going on at Holburn Head, similar to that at Wick, as illustrated by Fig. 13. The cliff at Holburn Head is, however, much higher than that at Wick, and the *débris* forming the mound is of much smaller dimensions.

The absolutely clean and new appearance of the rock surfaces and of the *débris* at Holburn Head leaves no room for doubting the statements made as to the winterly occurrence of storms capable of performing such work.

Examples from nature of what the waves of the sea can do are of so much interest and value that I feel I need make no apology for quoting at some length from Mr. Thomas Stevenson's description of what he saw in Zetland. He states—

"On the south-east side of Bound Skerry, about 370 feet from the low-water mark, and at a height of 62½ feet above its level, there occurs a remarkable beach of angular blocks, varying in size from about 9½ tons downwards, and huddled together just as one would have expected to find had they been elevated only a few feet above the high-water level.

"Towards the north-east, at the level of 72 feet above the sea, in addition to many smaller blocks which had evidently been recently detached, there was one 5½ tons in weight. It presented the appearance of recent detachment, having a fresh, unweathered look. Within 20 feet of the spot where it lay there appeared a comparatively recently formed void in the rock, which, upon examination and comparison by measurement, was found to suit exactly the detached block. Here, then, was a phenomenon so remarkable as almost to stagger belief—a mass of 5½ tons not only moved at a spot which is 72 feet above high-water spring tides, but actually quarried from its position *in situ*. But higher up still there was another detached rock, weighing no less than 13½ tons, tilted up in a peculiar position, and underneath which numerous angular masses had been wedged, obviously by aqueous action. This great block was, however, unlike the one first described, in bearing no traces of recent displacement. Though covered with lichen, and apparently long undisturbed, yet there can be no doubt that it, too, had been separated from the parent cliff, and been tilted up into the position which it now occupies by no other agency than that of the sea, the high-water margin of which is 74 feet below it."[1]

Lest the reader should be inclined to underrate the power of sea-waves, in consequence of what has been said in regard to the raising of land and glacial action, it may be well now to give a few examples of wave-power as actually witnessed during the construction of sea-works.

The Ymuiden breakwaters (Holland) are vertical, or nearly vertical, structures, with mounds of concrete blocks, termed "wave-breakers," on the seaward side. These mounds are composed of blocks weighing from 5 to 10 tons each, thrown pell-mell into the sea. The mound has a slope of about 1½ horizontal to 1 vertical, and is surmounted by a row of 20-ton blocks.

During one gale, one of these 20-ton blocks was lifted by a wave to a height of 12 feet (vertically up the face of the pier) and landed upon the top of the pier, which was 4 feet 10 inches above high water. The following waves knocked it over into the harbour. A similar block was lifted 10 feet, and landed on the top of another one.

During another gale at the same place, a "header" block, in the seaward face of the pier, measuring 7 feet in length, and presenting a face to the waves of 4 feet by 3 feet 6 inches, was started *forward* out of its place to the extent of 3 feet by the stroke of a wave compressing the air at the back of it. This block weighed about 7 tons, and the top of it was at the level of low water. It had three courses of concrete blocks, each 3 feet 6 inches in thickness, resting upon the top of it. These were all set in Portland cement mortar; but the course to which the block in question belonged was built dry, *i.e.* not set in cement, as were also those below it; the joints were, however, fairly close. The length of pier in which this occurred was finished, excepting that the blocks required to form the "wave-breaker" had not been deposited.

On more than one occasion considerable lengths of *courses*, the full width of the pier, composed of blocks weighing 5, 7, and 9 tons, all of which were set in Portland cement mortar, and tied together by strong wrought-iron cramps formed of 2-inches-square iron, were displaced and washed over into the harbour.

On other occasions, when the blocks were not disturbed, the

---

[1] "The Design and Construction of Harbours," by Thomas Stevenson.

UNIVERSITY OF TORONTO
[illegible] CIVIL ENGINEERING

permanent way rails (Vignole's section) upon the piers, although cramped to the blocks, were torn off; and in some cases, where the cramps could not be wrenched out or broken, the rail itself was torn away from them, leaving behind the piece of rail flange which was held by the cramp.

At the Manora breakwater, during one monsoon, seven 20-ton concrete blocks, which had been placed on the roadway of the breakwater for the purpose of sheltering the "Titan," were displaced, four of them being upset, and the remaining three made to skid some feet by the stroke of the sea. The roadway of this breakwater was, however, exceptionally low, being only about 2 feet above high water of spring tides.[1]

At Wick, during one storm, two stones, one weighing 8 tons and the other 10 tons, were thrown over the parapet of the breakwater, the top of which was 21 feet above high water.

Enormous blocks of concrete, weighing respectively 1350 tons and 2600 tons, were also displaced there; but, from a personal inspection of the work, and from descriptions given to me by those who were engaged upon it during construction, I believe that the displacement of these masses was in a great measure due to the failure of the foundations. It would, therefore, probably not be correct to attribute their disturbance entirely to wave-stroke, heavy as it undoubtedly must have been.

In reference to the above, Mr. Parkes said—

> "I would direct attention to the exceptional character of this case, *and to the impossibility of ascertaining all the conditions which might have contributed to so extraordinary a result.* Had this been simply the largest instance on record, standing at the head of a series of cases approaching to it by gradations, I would have been more disposed to draw general conclusions from the fact. But it seems to stand alone. To argue from it would be to condemn as dangerous every sea-barrier in existence, and to contradict the most trustworthy results of experience."[2]

At Alderney, stones of 9 tons' weight were lifted by the force of the waves from the foreshore, or seaward slope of the mound, and thrown over the top of the wall, a height from where they originally rested of 45 feet.[3]

At the Dhu Heartach lighthouse, off the west coast of

---

[1] The surface of this breakwater is now below high water, owing to settlement having taken place.

[2] *Min. Proc. Inst. C.E.*, vol. xliii. p. 52.

[3] Ibid., vol. xxxvii. p. 90.

Scotland, fourteen stones, each weighing 2 tons, secured by joggles and laid in Portland cement at the level of 35 feet 6 inches above high water, were, during a summer gale, torn up and swept away by the waves.[1]

Heavy seas have struck the iron tower on the Fastnet rock, on the coast of Ireland, although founded on a rock the top of which is 70 feet above high water, and the face almost perpendicular.

In the year 1887, Sir James N. Douglass, when giving evidence before the committee appointed to inquire into the desirability of electrical communication between light-vessels, outlying lighthouses, and the shore, in reply to a question put to him, said—

> "I do allude to the force of the sea, which is almost incalculable. I can tell you one circumstance which occurred in building the first Bishop Rock lighthouse, which was afterwards destroyed during a storm. We had landed a portion of one of the iron columns 23 feet long and weighing over 3 tons, and were arranging to place it in its socket, when the wind and sea increased so suddenly that we were compelled to leave the rock; but being very anxious to save the column, as its loss would have involved serious delay to the work, we did all we could to secure it. The lower part of one of the columns was already fixed in the rock at about 6 feet from its *lee* edge; we therefore placed the column just landed close to it over the edge of the rock, and nearly vertical, with its foot resting on a projecting bench, and there it was well lashed with ½-inch chain to strong eyebolts; the top end was also lashed in the same manner to the fixed column, and it was considered to be perfectly secure until we could return. After three days we were able to sail round the rock, with a heavy sea still running, when, to the amazement of my father, who had forty years' experience of sea-work, and of all who witnessed it, we saw that the column had been tossed up 20 feet on to the top of the rock, where it was held by the chain-lashing at its upper end to the fixed column, and was swaying about horizontally like a piece of timber. When we landed two days afterwards, we found another remarkable effect of the storm. In a hole partially sunk in the rock for one of the columns, 2 feet 6 inches diameter and 3 feet 6 inches deep, the blacksmith had left his anvil, weighing 1½ cwt.; this anvil had been washed out of the hole. When the blacksmith, who had served many years at similar work, discovered his loss, he exclaimed that the devil himself had been there."

---

[1] *Min. Proc. Inst. C.E.*, vol. xlvi. pp. 6, 7.

Sir James Douglass states that the heaviest seas he has experienced were on the west coast of England, about the Land's End and the Scilly Islands. In the latter place a piece of rock had been moved weighing 200 tons, and that not in the most exposed situation. He would expect that in the most exposed part of the coast a block of 300 tons might be disturbed by the heaviest seas.[1]

During the construction of the Wolf Rock lighthouse, a wrought-iron crane was erected on the tower for setting the work. At the close of the working season (1866), the bare post of this crane—*a wrought-iron cylinder* 16 inches in diameter, and the metal of which was 1¼ inch in thickness—was left in position, standing 20 feet above the masonry and 23 feet above high water of spring tides; but during the winter it was broken off flush with the surface of the work. When an examination was made of the material at the fracture, it was found to be of excellent quality.[2]

Almost every one who has been employed in the construction of sea-works in exposed positions, could supplement what has been said by stating his own experience; and it is scarcely too much to say that, however much may be written on the subject, only those who have had actual experience of what the power of a storm-wave is can adequately appreciate it.

Mud as an Indication of Exposure.—The late Mr. Thomas Stevenson, in his work on the "Design and Construction of Harbours," gives some interesting facts in regard to mud as an indication of the measure of exposure of a site, and points out that the level below low water at which mud reposes is proportionate to the amount of exposure, and consequently to the greatest height which waves are likely to attain in any given locality.

While admitting the value of the presence of mud as an indication of the extent of exposure, *when taken in conjunction with other physical conditions,* I am scarcely prepared to go so far as Mr. Stevenson in regarding it as "both a delicate and certain test of the limits of the utmost possible extent downwards to which the disturbance originating at the surface has reached."[3]

If we take a tub full of water, and place some mud in it, we may set up a miniature storm by agitating the water; and if this agitation be continued long enough, and sufficient force be employed, the whole of the mud will be lifted from the bottom and be held in suspension. A short time after this little storm has ceased, the mud will have settled to the bottom again, and will be there as if nothing had happened.

---

[1] *Min. Proc. Inst. C.E.*, vol. xxxvii. p. 373.

[2] Ibid., vol. xxx. p. 14.

[3] "Stevenson on Harbours," p. 15.

If we place the tub under a tap and let water run into it so that it overflows the sides, and then stir it up, the mud will be carried out of the tub by the overflowing water, and the water in the tub will gradually clear itself. It is therefore evident that, in order to get rid of mud, the agitating power must be accompanied by a transporting one.

In many bays, currents, if they exist at all, are very feeble. Under such a condition, it is quite possible for mud to exist where the water is comparatively shallow, notwithstanding that at times it may be disturbed by very heavy seas.

In Algoa Bay (South Africa), fine soft mud exists at the bottom in many places at depths of only 4 or 5 fathoms below low water.

The waters of this bay—which is open to the Indian Ocean, and exposed to heavy storms—are frequently much discoloured by this and by fine sand. There is no current where this mud lies, excepting an occasional surface-current set up by wind, so the mud is not carried away, but merely subsides when the disturbance ceases.

I have witnessed this on many occasions, and think it well to record the circumstance in order to show that, under the conditions named, the mud-test of exposure would be of little value, or might even lead to erroneous conclusions being arrived at.

In Reid's "Law of Storms," p. 181, I find Captain Webb, describing a typhoon in the China Sea, says, "At daylight we were in 12-fathoms water, with the sea, *which was as much mud as water*, breaking entirely over us."

Even where currents exist which are capable of removing mud when agitated, it seems possible that, after the mud has been scoured away from an exposed site through the operation of a great storm, a fresh supply may be brought by rivers or by other agency, and be deposited during the long interval of years which usually elapses between the occurrence of great storms, so that, however useful the mud-test may be in such localities as those referred to by Mr. Stevenson, it is an indication which, in my opinion, ought to be viewed with great caution. It is scarcely necessary to say that the absence of mud proves nothing.

General Remarks on Exposure.—I think it will have been gathered from the foregoing that, in forming an opinion as to the exposure of a site, it will be well not to arrive at conclusions too hastily, but to give due consideration to the various physical features of the site, such as the configuration of the coast-line and sea-bed, depth of water, both on the site of and for a long distance to seaward of the proposed works, range of tides—observing any special features which may be peculiar to them—direction and strength of currents, length of fetch, direction of heaviest recorded storms and waves, usual sequence of gales, etc.

From such facts and features, coupled with a study of other local indications, an opinion, more or less reliable in proportion to the experience of the observer, may be formed of the worst that could happen under a combination of the most adverse conditions.

It is true such a combination might not happen more than once in a century, but it might, nevertheless, happen at any time, and the engineer ought to anticipate and make provision for the worst.

Since tradition, or even the memory of "the oldest inhabitant," cannot always be relied upon as infallible, it will be well, as far as possible, to verify any local information that may be obtained.

CHAPTER VI.

QUARRYING.

Selection of quarry site—Overburden—Drainage—Arrangement of quarries—Height of working face—" Strike " and " dip " of strata—Small-hole blasting—Weight of charges—Mine-blasting—Line of least resistance—Cranes, etc.—Steam and hand drilling—Consumption of steel—Forms of drills—Explosives—Seam-firing—Cutting stone by means of " plugs " and " feathers "—Charging bore-holes—Tamping—Firing by electricity—Lightning fuse—Safety fuse.

THE manner in which quarrying is conducted is so important a feature in the execution of sea-works, and may so materially affect their cost, that, although the subject may be considered as scarcely coming within the range of this work, I hope any inconsistency there may be in introducing it here will be overlooked.

I do not propose to describe quarrying generally, but merely wish to direct attention to such points as, I hope, may be of use to the young harbour-engineer.

The mode of quarrying stone for monumental or architectural purposes is, to a great extent, governed by conditions which do not affect sea-works, and need not therefore be referred to.

Selection of Site.—After having estimated the quantity of stone required for any work, due allowance having been made for waste, possible alterations in, or extensions of the proposed works, and so forth, the area of land to be taken for quarry purposes can be determined, the intended height of working face, having reference to convenience of approach and contours of the ground, having, as a matter of course, been duly considered.

A sufficient number of trial pits should be sunk over the surface of the contemplated quarry site, to furnish an accurate knowledge of the ground. Some of these may, with advantage, be carried down into the rock, with the view of ascertaining its quality, which can be done with more certainty in this way than by merely examining the surface or by taking borings. Where possible, exposed faces, old quarry workings, or buildings in which stone from the district has been used, should be carefully examined, with the view of ascertaining its "weathering" properties.

Overburden.—An important point for consideration in selecting a site for a quarry is the amount of "overburden"[1] which would have to be removed before the stone could be obtained. Seeing that the cost of removing this must generally be added to the cost of the stone, it is evident that, if the quantity should be large, it would represent a material increase in the cost of the work, and might point to the expediency of looking further afield for a more suitable site.

Since the disposal of overburden, when it has been removed, may entail the purchase of additional land, it will be necessary to roughly estimate the quantity. This calculation will be facilitated by the knowledge gained in sinking the trial pits before named.

It will generally be found desirable to lay out a quarry floor at such a level, and with such inclination (say 1 in 500, or even flatter), that it will drain itself. As, however, the quality of stone often improves as the depth increases, it may be found advisable to sink the floor to a considerable depth, and rely upon pumping to keep the quarry free from water. This latter system is adopted in nearly all the Scotch granite quarries, a very small pump being found sufficient, in most cases, to keep the floor dry. When, however, large quantities of stone are required, such an arrangement would be found to possess serious drawbacks.

A convenient and sometimes economical plan for disposing of "overburden" or other useless material, is to form an embankment with it upon the quarry floor as the quarry working advances, the cranes and lines for waggons being mounted upon the top of it. The working floor of the quarry may thus be 10 to 12 feet, or other convenient depth, below the crane floor. This will be governed by the quantity of rubbish to be disposed of, and may be varied from time to time as circumstances require. In thus disposing of overburden, etc., due provision for drainage, either by natural flow or by pumping, must not be lost sight of.

---

[1] Earth or other material overlying the rock; also called "baring," "tirr," etc.

Arrangement of Quarry.—The arrangement of lines of railway in a quarry is deserving of careful attention. In practice, I have found the most convenient arrangement, where the contours of the ground and other considerations will admit of its being adopted, is to lay the lines square to the quarry face, as shown in Fig. 16, A, so that they follow up the work as it proceeds, without disturbance or sluing. If space will not admit of curves being laid in from the main line, turntables may be substituted. These were used in the extensive quarries at Holyhead, and worked satisfactorily.

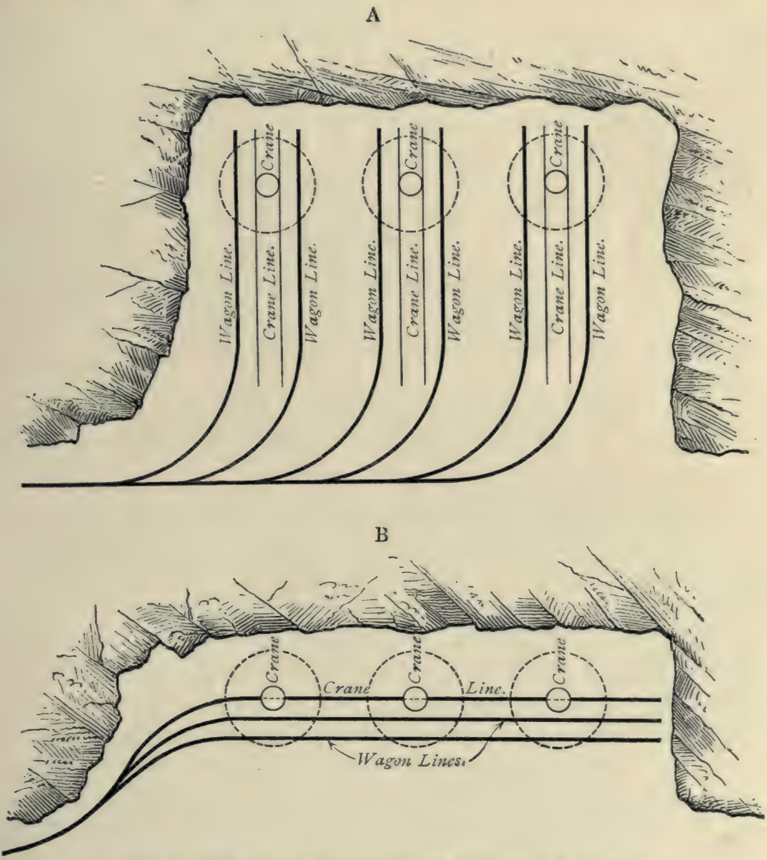


FIG. 16.—Plan showing arrangement of lines of railway in quarries.

When lines are laid, as they often are, parallel to the working face of the quarry, as at B, Fig. 16, it becomes necessary to slue them periodically as the working face recedes. This arrangement, however, soon gives trouble. The curves become too sharp, and the lines are distorted by repeated sluing, so that from time to time they require to be taken up and relaid; the quarrying operations, meanwhile, being seriously interrupted.

Working Face.—Whenever possible, a good working face should be obtained, and in opening out a quarry this should be borne in mind and arranged for.

When the face is very high, it is sometimes worked in "lifts" or "benches" of from 40 to 50 feet in height, especially where small-hole firing is resorted to; but when mines are used, the whole height of face is generally dealt with in one blast.

"Strike" and "Dip" of Strata.—The direction of the "strike" and "dip" of the strata must be carefully considered in laying out a quarry. In granite quarries, and others in igneous rocks, the run of beds and joints is very uncertain, although in some instances they display a regularity approaching to that of stratified rocks.

When the "dip" and "strike" of rock can be taken advantage of in quarrying, it will be found to greatly facilitate work.

Blasting.—Quarrying is commonly conducted by firing comparatively small charges of blasting-powder, or other explosive, placed in holes drilled to such a depth as circumstances may require.

The weight of charge must depend greatly upon the length of the line of least resistance, the arrangement of beds and joints of the stone, and the extent to which these have been taken advantage of in deciding upon the position of the charge. A common practice, in determining the amount of powder to be used, is to cube the line of least resistance in feet, and divide by a coefficient which varies according to the nature of the rock to be blasted, and which can only be determined, with accuracy, by actual trial and experience.

For hard, heavy, compact rock, such as granite, quartz, etc., the coefficient will be about 16 or 18, whereas for softer and lighter descriptions of rock it may vary from 20 to 30.

In some blasts at Holyhead, where the rock is of hard quartzite, the coefficient adopted was from 10 to 12; whereas at the celebrated and successful blast made at Round Down Cliff, Dover, many years ago, on behalf of the South-Eastern

Railway Company, where the rock is chalk, the coefficient adopted was 32.

In this mine, 18,500 pounds of powder were used, and the chalk rock thrown down amounted to about 700,000 tons, being very nearly 38 tons per pound of powder. This was, however, an altogether exceptional operation, and the nature and position of the projecting mass of rock removed were such as to admit of the powder exerting its power to great advantage.

In ordinary quarrying, in hard rock, the yield per pound of powder usually amounts to from 4 to 6 tons.

After having ascertained, approximately, the weight of a charge by the foregoing rule, it is well to check it by estimating, as nearly as possible, the amount of rock which it is expected the blast will throw out, and, in the case of hard compact rock, allowing one pound of powder for every 4, 5, or 6 tons of rock, as the arrangement of joints and other circumstances may indicate.

In this way, after a little experience has been gained, the correct weight of charges may be decided with some degree of accuracy.

The system of measuring the charge by taking some proportion, say $\frac{1}{3}$ or $\frac{1}{4}$ of the depth of the hole, regardless, to a great extent, of the size of hole or weight of rock to be moved, is obviously a careless mode of apportioning a charge, which should not be allowed.

In some cases, it may be found convenient to charge the holes or mines somewhat heavily, in order to break up the stone, and thus obviate, to some extent, the necessity for doing so afterwards by means of wedges, hand-drilling, or plaster-firing.[1]

In estimating the space required by a charge of any given weight, 30 cubic inches should be allowed for each pound of powder.

Some care is necessary in deciding which is the line of least resistance, because it may be greatly affected by the arrangement of joints, and the inclination of the beds of the rock.

Although vertical holes involve a greater length of boring than horizontal holes, they will usually be found to possess many advantages which the others do not. They are easier to drill, load, and tamp; and the line of least resistance is not, unless in very short holes, that of the hole, which is manifestly weaker than the solid rock, no matter how well the tamping[1] may have been done.

---

[1] Laying small charges of guncotton or nitro-glycerine compound upon the surface of stones, covering them with earth or other suitable substance, and then firing them.

At Holyhead, quarrying was conducted for a year or two in the usual way by small-charge firing; but it was found impossible to maintain a sufficient supply of stone for the breakwater works by this method. Shafts were consequently sunk, or headings driven, and blasting on a very large scale was resorted to.

Headings were ultimately adopted, in preference to shafts, in consequence of the height of the quarry face, and the greater facility with which they could be driven. They were also more easily kept dry, and the ventilation was better.

As much as 130,000 tons of stone were, on one occasion, thrown out by a single blast, the charge being 21,000 pounds of powder. The yield of rock was, therefore, rather over 6 tons per pound of powder. On an average, however, about 4 tons of rock were thrown out per pound of powder used; but in confined corners, or where the rock was much "bound," a "shot" would often not yield more than one-half of this quantity.

In small-charge firing, a good deal of time is sometimes wasted by the removal of men, horses, and plant from the quarry, or into safe positions, while the charges are being fired. Delay from this cause may be lessened, or altogether prevented, by firing the "shots" during meal-hours, or when the quarriers have left work for the day; also by the use of travelling cranes, which can easily be moved out of danger.

In mine-firing, the rock is sometimes dislodged in such large pieces that the firing of small shots has to be resorted to in breaking them up into manageable sizes. In consequence of this, some of the inconveniences attendant on small-blast firing are incurred.

Quarry Plant.—Since the use of large blocks of stone in sea-works is often desirable, or indeed in some situations absolutely necessary, the quarry plant, as well as the waggons for conveying the stone to the works, should be fully equal to deal with lumps of from 10 to 12 tons, whenever the magnitude of the work and financial considerations will admit of it. It is, however—even from an economical point of view—well to provide good plant at the outset of a work.

---

[1] See p. 102.

Although the power of the cranes to be used in a quarry must greatly depend upon the weight of the stones which they will be required to lift, this is not, in all cases, the only consideration. After the firing of a "shot," when the "output" is lying in a confused heap, a powerful crane will often be found of the utmost service in dragging out the larger lumps and distributing them to the stone-cutters for splitting up into such sizes as may be required. It is not always easy to estimate what power is required to dislodge such stones from a heap; but where work of this kind is anticipated, it would scarcely be prudent to provide cranes of less power than I have named, smaller auxiliary cranes being provided, if necessary.

The cranes—which are most convenient if of the travelling type, inasmuch as they can follow up the work and move out of danger, as has already been pointed out—should command two or more lines of way, by which arrangement one line at each crane will always be clear to receive the empty waggons on their return.

In order to protect cranes from injury when they are not able to run back under shelter, strong shields, of sufficiently large area, should be provided.

These may be made of timber, or other suitable material. They are usually hauled up in front of the cranes by the cranes themselves.

Fig. 17, p. 96, is copied from a woodcut which illustrates Mr. Harrison Hayter's paper on the Holyhead new harbour (*Min. Proc. Inst. C.E.*, vol. xliv.). It shows the arrangement of galleries and charges in a blast which produced 120,000 tons of stone.

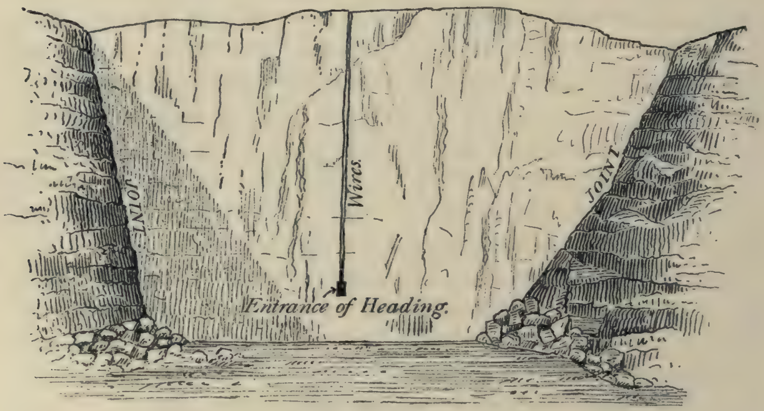
For much of the information which this chapter contains relative to the quarrying operations at Holyhead, I am indebted to the above paper, and also to some pleasant conversations which I had with Mr. Hayter—my old friend and chief—while visiting the Holyhead quarries in the autumn of 1889.

In driving galleries, or headings, they should always be made to take one or more rectangular turns, in order to prevent any possibility of the tamping being blown out.

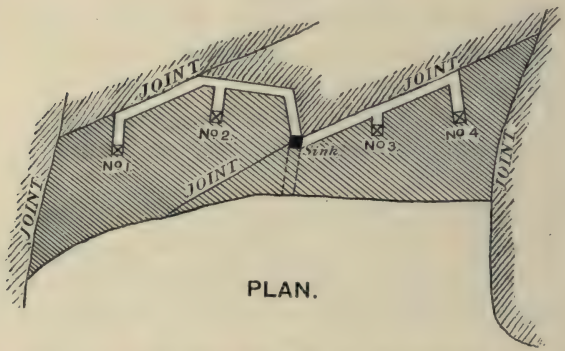
The average rate of progress in driving the headings at

Holyhead was five feet per week, four men being employed. The cost varied from 10*s.* to 25*s.* per lineal foot.

Much labour and expense will be saved by placing the charges well below the level of the quarry floor—say from 3 to 4 feet. If this be not done, inconvenient peaks or lumps of rock will remain, which may subsequently have to be removed at considerable cost.



ELEVATION.



PLAN.

Fig. 17.—Plan showing arrangement of galleries, etc., for large blast at Holyhead Quarries. Height of face, 115 feet; length of face, 210 feet; length of heading, 125 feet; depth of sink, 23 feet, being 3 feet below level of quarry floor. Length of chambers—No. 1, 12 feet; No. 2, 12 feet; No. 3, 6 feet; No. 4, 15 feet. Charges—No. 1, 4200 lbs.; No. 2, 4500 lbs.; No. 3, 2300 lbs.; No. 4, 5000 lbs.; total, 16,000 lbs. Line of least resistance, average 23 feet. Produce, 120,000 tons.

If the quarry floor is kept well below that upon which the cranes and waggons travel, in the manner before mentioned, no inconvenience from this cause will be experienced.

Boring Holes for Charges.—This is generally done either with a "jumper" or with a drill, which is held and turned by one man while two other men strike the head of it.

The term "jumper" is sometimes applied to long drills, which, when a hole becomes deep, are used as jumpers; *i.e.* lifted and struck upon the rock, the weight of the drill and the impetus given to it being, in such cases, as effective as striking the head of it with hammers.

"Jumpers," properly so called, are usually from 6 to 7 feet in length. They are sharpened at each end, and are swelled out into the form of a thick disc or ball at about half their length, so as to add to their weight, and assist in giving them a rotatory movement. In some quarries, where the rock is very hard, they are not found to answer so well as drills; but, where applicable, more work can, as a rule, be done with them in a given time than with drills.

It is usual, in boring rock, to pour water into the hole. This assists the operation by keeping the drill cool, and enabling it to retain its edge better than it would otherwise do. Even the hardest kinds of rock seem to cut better when wet than when dry. The water also forms the dust and small fragments into a paste, in which form they are more easily removed by the "spoon," or scraper.

If it be required to thoroughly clean out the hole, an extra quantity of water is put into it, which is afterwards removed, in the form of thin mud, by means of a piece of rag (old powder bags), frayed rope, or other suitable material passed through the eyed end of a rod. The holes should always be well dried out before powder is inserted.

In the quarries at Port Elizabeth (South Africa), from which the stone was procured for the harbour-works there, the rock was quartzite, similar to that at Holyhead. The drilling was performed partly by steam and partly by hand.

The steam-drills were of the Ingersoll type, and the drills used with them were arranged in sets of six, viz. $3\frac{1}{2}$, $3\frac{1}{4}$, 3, $2\frac{3}{4}$, $2\frac{1}{2}$, and $2\frac{1}{4}$ inches. They thus diminished at the rate of $\frac{1}{4}$ inch per drill, this being necessary for purposes of clearance. A drill would seldom bore more than 18 to 20 inches without being sharpened.

Much time was occupied in moving the machines about the quarry, and placing them in position for drilling, also by stoppages for repairs. Each machine drilled on an average 84 feet per week. The greatest depth drilled in one day of 10 hours, by one machine, was 26 feet.

The form of drills used was that of a cross; but they were costly to make and sharpen. Flat drills of the ordinary form did not answer, on account of their corners wearing away too fast, especially when boring holes that were horizontal, or nearly so. This was obviated, to some extent, by increasing the wearing surface, but they were not found to work so satisfactorily as drills of the cross form.

The cost per lineal foot of drilling by hand was only about one-half of the cost of drilling by steam; but the hand-drills were only 2 inches wide, diminishing slightly to give clearance as the boring advanced; whereas the steam-drills were 3½ inches wide, diminishing to about 2¼ inches at the bottom of a hole, say, 20 feet deep.

The larger holes, drilled by steam, enabled the charges to be placed well down at the bottom, which, especially in holes that were horizontal, was found to be of great advantage. Indeed, the quantity of rock thrown out by charges placed in the large machine-bored holes was about double, per lineal foot of hole, that thrown out by charges placed in the smaller hand-bored holes. The cost of drilling by steam and hand, *per ton of stone*, was therefore about equal.

Some very good results were obtained by simultaneously firing, by means of electricity, groups of 5 or 6 charges, placed in machine-bored holes.

The speed with which drilling can be done is necessarily governed by the texture of the rock and the size of the drill used.

The following statement will give the reader a fair general idea of the speed of drilling by hand in hard rock:—

Place.	Description of rock.	Size of drill.	No. of men.	Usual average depth drilled per hour.
		inches.		feet.
Holyhead	hard quartzite	1½	3	1·17
Port Elizabeth (South Africa)	„	2	3	1·04
Peterhead, N.B.	granite	1½	3	2·17
„ „	„	2½	3	1·43
Dalkey,[1] near Dublin ...	„ (very hard)	1¾	3	1·20
„ „ ...	„	2	3	0·80
„ „ ...	„	2¼	3	0·60
„ „ ...	„	2½	3	0·50
„ „ ...	„	3	3	0·40
Plymouth, district	hard limestone	1½	3	6·00
„ „	„	2	3	4·50

[1] "Blasting and Quarrying of Stone," Burgoyne.

Opinions differ as to the weight of hammers best suited for drilling. Some quarriers use hammers weighing as much as 16 or 18 lbs. for the larger drills—say from 2 to 3 inches—and lighter hammers for the smaller ones.

In the Aberdeen and Peterhead districts, long hammers, measuring about 10 inches in the head and weighing about 9 lbs. each, are almost universally used, and are considered to work better than those of greater weight.

In my opinion, a man is what is termed "overtooled" with a hammer of 16 or 18 lbs. weight, and I much prefer those which are not so heavy.

Quarry drills are now generally made of solid octagon cast-steel, the sizes commonly used varying from 1 to 1¼ inch, according to the size of drills. For small drills, employed in drilling plug-holes, ⅝ or ¾ inch steel is used.

The waste of steel at the head of solid steel drills is so much less in quantity than the waste of iron used to be, when the drills were made of iron and steeled only at the point, that, notwithstanding the higher price of steel, it is found to be economical to make the entire drill of it; moreover, the labour and cost of constantly "steeling" the point is thus saved.

With good smiths, the consumption of steel in a quarry is very small.

In the Port Elizabeth quartzite quarries, it amounted to 0·024 lbs. per ton of rock quarried, and averaged 0·06 lbs. per foot of hole drilled. The greater portion of this was, however, chargeable to the steam-drills, which were much more wasteful of steel than the hand-drills.

In drilling granite of ordinary hardness, such as that in the Peterhead district, by hand, the consumption of steel is only about one-third of the above.

In drilling hard rock, the drills usually require to be sharpened once for each 12 or 18 inches bored.

Forms of Drills.—The forms of drills shown in Fig. 18, p. 100, are those which, from experience, I have found well suited for boring hard rock by hand. For softer rock similar drills may be used, but the angle of their cutting edges should be made more acute.

Standard gauges ought to be worked to in making and sharpening drills, otherwise they are very liable to give trouble by becoming jammed in the holes.

Drills should be arranged in sets, and their widths should diminish at the rate of about $\frac{1}{16}$ inch for every 18 inches drilled in hard rock. A somewhat smaller allowance will suffice in softer rock, as the drills do not wear away at the sides so fast. Thus in a hole 18 feet deep, assuming it to be started with a $2\frac{1}{2}$-inch drill, the last drill would measure only $1\frac{13}{16}$ inch.[1]

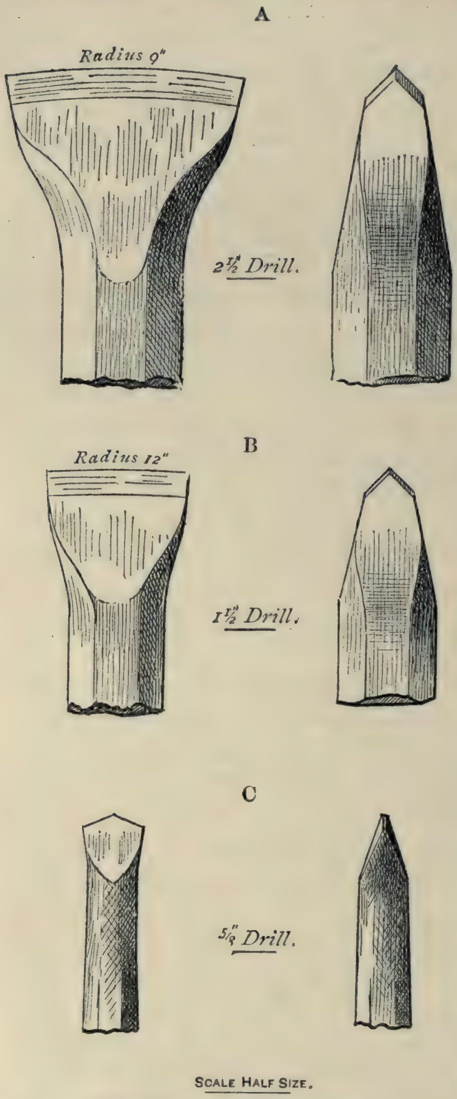


Fig. 18.—Drills used in quarrying.

Drills as shown at A and B, Fig. 18, are used for deep holes. The cutting edge of the first or entering drill is rather more rounded than that of the following drills, it being found easier to bore the first length of a hole true with a drill thus formed than with the squarer tools. Drills of the forms shown at A and B cut triangular holes. Diamond-pointed drills (C) cut faster than square or slightly rounded tools. They cut circular holes, and are found more convenient for "pitching" holes than those of other forms. They will not, however, stand heavy hammering, and are chiefly used for drilling the short plug-holes—say from 3 to 4 inches deep—by means of which blocks of stone are cut or cloven with "plugs and feathers." Such holes are drilled in rows, and upon their accuracy, not only of position, but also of direction, the success or failure of any "cut" will greatly depend.

---

[1] The steam-drills mentioned on p. 97 were for the most part used for boring horizontal holes, the wear on the sides of the drills being thus much greater than in the boring of vertical holes.

Explosives.—Dynamite, guncotton, and other quick explosives, will be found to crack granite and similar hard rock for a considerable distance from the charge. When rock is only required as rubble, these explosives may often be used with advantage; but when blocks of stone are required for ashlar-work, their general use is inadmissible. Insipient cracks thus formed are often very difficult to detect, and in some cases are only discovered when the stone parts under the mason's hammer, possibly after a considerable amount of labour has been expended upon it.

In driving headings for mines, small charges of guncotton or of nitro-glycerine compounds will be found of great service, they being, as a rule, far superior to powder for such work.

When rock is liable to be too much broken up by ordinary blasting, seam-firing may be resorted to.

Seam-firing.—In the first instance, holes are drilled along the line of the seam or joint which it is intended shall form the limit of the mass to be dislodged. The charges are then so proportioned that they shall only have power enough to push the mass forward to the extent of a few inches. When this has been done, and a sufficient time—at least four hours—allowed to elapse to ensure safety, powder is deposited in the seam, and tamped with such suitable material as may be at hand. Tamping seams is by no means an easy or perfect operation, because, owing to their narrowness and irregularity, it is often impossible to ram the tamping properly, and we have, therefore, to be satisfied with the best we can do. In seam-firing, extreme local pressure and shock are avoided, and the energy of the exploding charge is much more evenly distributed over the back of the mass, which is thus heaved out with but little noise or disruption. This system is largely adopted in quarrying granite for monumental purposes, and I have found it very useful where it has been difficult, from the output of ordinary blasts, to find sufficient good stone for large ashlar-work.

Some kinds of rock may be readily quarried by drilling lines of holes, and bursting off pieces, of the dimensions required, by means of "plugs" and "feathers" or wedges. This system cannot well be adopted excepting where the rock is stratified. It is, however, extensively resorted to in many sandstone and freestone quarries. I was much interested in watching hard black schistose rock being quarried in this manner for the harbour works at Wick, splendid blocks of the requisite sizes being thus obtained, which were as well-shaped as though much mason's labour had been bestowed upon them.

When lumps of hard rock require to be split with great accuracy, holes, spaced from 4 to 12 inches apart according to the nature and size of the stone, are drilled in rows with $\frac{3}{4}$-inch to $\frac{7}{8}$-inch drills almost through the stone, long plugs and feathers being used for bursting the stone.

Small steam-drills, mounted upon frames on which they can travel, are found very expeditious and satisfactory for this work, the holes put in by them being far truer than those drilled by hand.

In granite one man drills about 15 feet of such holes in 10 hours; while one of the small steam-drills will put in 80 to 100 feet in the same time.

Loading Bore-holes.—Before inserting the powder, the bore-hole should be well cleaned out and dried.

Vertical holes are easily charged by pouring the powder into them. This is usually done through a tube and funnel, so as to prevent the powder adhering to the sides of the hole.

Horizontal holes, or those inclined upwards, are best loaded by first making up the required charge into one or more cartridges of convenient size, which may then be easily rammed in. Horizontal holes are sometimes loaded by means of a cylindrical scoop attached to the end of a rod. The edges of such scoop are brought well up, so as to leave only a slit along the top. When it reaches the bottom of the hole, half a turn is given to it prior to its withdrawal, by which means the powder is emptied out.

When holes cannot be properly dried, it is necessary to make up the powder into water-tight cartridges. Wet holes, however, usually occur at or below the floor-level, in which position one or other of the nitro-glycerine compounds, which are unaffected by wet, may be employed with advantage.

Tamping.—I have had occasion to refer to "tamping" before, and it will be understood that by it is meant the filling of the bore-hole after the charge has been inserted. It is an important point in quarrying, and, if improperly done, may greatly reduce the effect of the charge, or lead to accident.

The best materials for tamping are those which are cohesive, impervious, and moderately hard—such, for instance, as good dry clay, powdered brick *slightly* moistened, and some kinds of decayed rock.

Sand, stone-chips, and such-like, are not good materials for tamping, and should not be used when other and more suitable material can be procured. Stone-chips should on no account be used near the charge. The tamping material should be put down the bore-hole in small pieces, which should be well rammed with a copper or wooden rod ; iron must on no account be used.

For a length of, say, 12 inches from the charge, it is well not to ram too hard for fear of disturbing the fuse, or breaking its connection with the charge; moreover, nothing should be used in the tamping which would be likely to cut or injure the fuse, as a miss-fire might thus be caused.

When using dynamite or other quick explosives, the same care in selecting material for tamping is not necessary, fine sand being quite effective. With nitro-glycerine compounds, even water may be used.

In the mine-blasts at Holyhead, the powder was usually built in for a few feet with dry rubble, the remainder of the headings being rammed with clay.

Firing by Electricity.—Large blasts are usually fired by means of electricity.

The batteries used for this purpose are of various designs, but the methods adopted for igniting the charges are somewhat similar. This is usually done by passing a sufficiently strong electrical current through an exceedingly fine platinum wire, whereby it is made red-hot or fused. This fine wire, which is contained in a specially constructed fuse, is included in the circuit, and is surrounded by a highly inflammable substance, which the heated wire ignites. Fuses of this description are called "low tension" or "quantity" fuses.

In what are termed "high-tension" fuses, the ends of two copper wires are brought to within about $\frac{1}{16}$ or $\frac{1}{20}$ of an inch of each other, there being thus a break in the circuit. In this break the priming composition is placed. It is fired by the spark which is generated by the passage of the electric fluid from one wire to the other.

When a charge is to be fired one or other of the above fuses is inserted, just as the end of a piece of ordinary slow fuse would be, the wires from it being coupled up with those from the battery. The charge may then be fired at pleasure. The battery wires ought on no account to be connected with the battery until all is ready for firing.

Fuses.—A good substitute for electricity in firing several charges simultaneously has been invented by Messrs. Bickford, Smith & Co., the well-known fuse manufacturers.

It consists of several lengths—corresponding with the number of "shots" to be fired—of what is termed "instantaneous" or "lightning" fuse, the ends of which are brought together into a small cylinder called an "igniter." This contains an explosive disc, against which the ends of the several lengths of instantaneous fuse rest, and which ignites them all simultaneously when fired by means of a single ordinary safety-fuse, which enters the "igniter" at the opposite end. The other ends of the instantaneous fuses are placed in connection with the several charges in precisely the same way that ordinary fuses would be.

The instantaneous fuse burns at the rate of 150 feet per second; consequently, if the lengths leading to the several charges measure approximately the same, the charges will all be fired at the same instant.

When electricity is not used, single charges are generally fired by means of the ordinary "Bickford" safety-fuse. This fuse is supplied in several qualities to meet the various conditions under which it may be employed. The rate at which it burns varies slightly, but is generally from 2 to 3 feet per minute.

UNIVERSITY OF TORONTO
DEPARTMENT OF CIVIL ENGINEERING
[illegible] and SURVEYING

CHAPTER VII.

MATERIALS.

SECTION I.

General remarks—Erosion—Eroding agents—Power of moving shingle—Sand-blast—Danger of open joints in structures.

In selecting materials for sea-works, the two principal qualities to be sought after are durability and high specific gravity. The latter of these has more especial reference to the various descriptions of stone and concrete.

Durability is affected by erosion, as well as by changes of temperature and chemical action, which latter may be taken to include ordinary decay.

The chief eroding agents are sand and shingle, set in motion by the waves of the sea and by currents; but rain and frost, and the acids contained in the atmosphere and in sea-water, often play an important part in the process of erosion by disintegrating and loosening the surface particles. The same may be said of excessive heat, especially when acting upon surfaces which are intermittently wetted.

In some localities floating ice is a destructive agent; so also is the ice which at times accumulates in large masses upon the face of piers situated in cold regions. I have known such ice, in falling away from the face of a pier, take with it a slab of concrete several inches in thickness, which it had detached from the main mass.

The amount of work performed by waves, in rolling about the stones upon a shingly beach and rubbing them against each other, is indicated in some degree by the familiar grinding noise which is made. The power of such a "mill" can, however, only be appreciated by those who have carefully noted it. It is astonishing how soon pieces of the most refractory rocks, such as quartz or granite, become rounded and worn down when subjected to such action.

The rapidity with which concrete blocks, even of the hardest quality, are worn away by the motion of shingle in front of or amongst them is well known to most engineers; and blocks of granite, although much more durable than concrete, are similarly affected. In illustration of this, I give the following sketch, which represents a large red granite boulder—one of several—which until recently protruded from a shingle beach on the south side of Peterhead Bay.

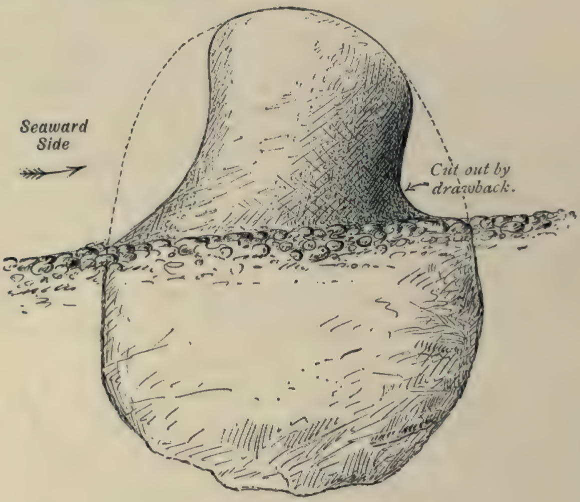


FIG. 19.

It must not be imagined that erosion by sand or shingle is due merely to their being rolled about by the waves, because it is a fact that they are taken up by them and dashed against opposing objects with enormous force. I have seen the face of a sea-wall, composed of hard 6 to 1 Portland cement concrete, starred by the impact of pebbles driven against it during a storm to such an extent that it looked almost as if it had been subjected to rifle-fire.

The projections which were left upon the large and very hard quartzite stones forming the sea face of the superstructure of Holyhead breakwater, have already been much reduced and rounded by the grinding of rubble and shingle against them.

The erosive power of sand is well illustrated by the "sand-blast." This consists of a small jet of air or steam carrying sand with it, and usually having a pressure of from 70 lbs. to 90 lbs. per square inch. It is used for various purposes, amongst which is the sharpening of hard steel files.

Glass bottles placed in a sand-drift will very soon have all the glaze taken off them, and the sharp edges of broken glass quickly become rounded under such conditions.

In the year 1891, an arrangement of low-pressure sand-blast was used for cleaning the marble exterior of the United States Assay Office in Wall Street, New York. In this instance, sand was driven against the work by an air-blast having a pressure of only 2 lbs. per square inch. This abraded 1 square foot of marble, to a depth of from $\frac{1}{32}$ inch to $\frac{1}{64}$ inch in one minute, and left a fresh clean surface. Great storm-waves strike with a force of more than 40 lbs. per square inch (p. 41).

Tidal or other currents, carrying with them sand and shingle, will often very quickly wear away the blocks forming a pier-head; special care is therefore necessary in selecting suitable material for use in such positions.

Sufficient has now been said to show the necessity of using none but the most wear-resisting materials in positions where they will be subjected to such erosive action as has been described, bnt I would like to say a few words upon the direct dynamical eroding power of the waves themselves.

On carefully examining sea-cliffs, or rocky shores exposed to heavy seas, evidences of erosion are easy to be seen. These have already been noticed in the chapter on exposure and wave-power; but it is not always by such intermittent violent assaults as are there described that the greatest effect is produced. Moderate gales, of frequent occurrence, carry on the work of destruction with none the less certainty because they do it more slowly and with less ostentation.

Wherever joints occur, either in rock or in artificial structures, both mechanical and chemical action proceed the fastest.

Apart from the inherent weakness of joints, the air or water confined within them, when struck by a wave, is converted into a very destructive agent. The air, under such circumstances, is compressed and forced along joints or seams, and, immediately upon the wave receding, it expands and tends to loosen and push out pieces of the rock.

UNIVERSITY OF TORONTO
CIVIL ENGINEERING
Structural

When water is confined in joints, the force of the wave-stroke is transmitted by it, and made to act over large areas on the same principle as a hydraulic press.

The failure of many sea-works may be attributed to this cause, blocks of stone or concrete, even on the harbour side of breakwaters, and the stone pitching of their roadways, having been frequently started out of their places by a heavy wave-stroke on the seaward face of the structure.

Changes of temperature, by causing expansion and contraction, form and open out joints, and thus assist the waves in their destructive work.

An experiment, showing how force suddenly applied is conveyed by water, even when unconfined, *i.e.* having its whole surface free, may be easily made by filling a small ordinary powder-keg with water, and exploding a copper detonating cap—such as those used for exploding dynamite—in the midst of it. The pressure exerted by the explosion of the cap upon the water is immediately transmitted to the sides of the keg, with the result that the hoops, and sometimes also the staves, are rent.

Mr. Mallet mentions another instance, somewhat similar to the above, which he thus describes—

> "During the progress of the experiments made by the French artillery at Metz to ascertain the penetration of bullets in water, a long rectangular *open-topped* trough, about 12 inches in width, the same in depth, and say 20 feet long, was formed of wood, one end being of india-rubber cloth. It was filled with water, and a common musket-bullet fired horizontally into the water through the india-rubber end. To the surprise of all, the trough was split to pieces, both the sides and the ends being thrown asunder."[1]

I will cite one other instance illustrative of the manner in which a sudden shock is conveyed by water.

Some years ago I had occasion to employ dynamite in removing a submerged structure. Charges varying from 16 oz. to 19 oz. were used. When these operations were initiated, it was not anticipated that divers, working at a distance of about 500 feet from the site of the firing, would be inconvenienced by it. They were, however, unanimous in stating that the shock of each explosion was almost sufficient to stun them; and diving, whilst blasting was going on, had to be discontinued.

---

[1] *Min. Proc. Inst. C.E.*, vol. xviii. p. 114.

From what has been said, it will be seen of what vital importance it is to prevent wave-stroke being transmitted in structures, in the manner described.

In Chapter V., p. 83, it was mentioned how a block weighing 7 tons was started out of its place by water-pressure or compressed air. On another occasion several adjoining blocks were forced outward on the harbour side of the breakwater at East London (Cape Colony), presumably from the same cause. Too much care cannot, therefore, be taken to ensure close and well-filled joints and beds in sea-works.

It is impossible to say where the mischief, originating in the withdrawal by the sea of a badly set face-stone, may end. When once a breach has been made in the face of a breakwater, it is amazing with what rapidity the work of destruction sometimes proceeds.

The large fronds of "sea-wrack" or "tangle" (*Laminaria digitata and L. saccharina*), with their thick and tough stems, when swayed to and fro by the waves, often tear out the pieces of rock to which they are attached, and then float away with them, or materially assist the waves and currents in transporting them.

It is curious to notice, after a storm, what a large proportion of the stems of the wrack which have been thrown upon the beach, have stones or pieces of rock—usually about the size of one's fist—attached to their roots. Often, however, much larger pieces of rock are detached and transported by seaweed.

Mr. Kinahan, in his communication on the "Carriage of Stones in Deep Water" (*Min. Proc. Inst. C.E.*, vol. lviii. p. 284), says—

> "At the end of the Tacumshin Æolins sand-ridge, there is, below the sloping shingle beach, a nearly flat sandy strand, usually free from blocks (of stone), which, on April 4, 1876, during low water, after a heavy gale from the south-west, was covered with blocks, having deep-sea weed attached, while on the slope there were other similar blocks. As the tide rose, these blocks began to drift landward, and in twenty-four hours nearly all the blocks were collected in horizontal lines."

Mr. Kinahan goes on to state that some of the stones weighed from 2 to 3 cwt. apiece.

Section II.—Stone.

Stone for sea-works should have high specific gravity—Basalt, granites, and syenites—List of stones—Indications of decay—Chalk, limestones, and sandstones—*Pholas dactylus*—Quartzite—Weathering qualities of stones—Iron-furnace slag used for constructing breakwaters.

It has already been stated (p. 105) that, in selecting materials for sea-works—other things being equal—preference should be given to those of high specific gravity. The reason for this is evident; inasmuch as, comparing blocks of equal weight, their displacement is inversely proportionate to their specific gravity, as is also the area exposed to the wave-stroke.

For example, a block of cast iron weighing one ton would contain 5 cubic feet, and would thus be represented by a cube the side of which would have an area of, approximately, 2·9 square feet. This block, immersed in sea-water, would weigh about 1920 lbs., and a wave striking the face of it with a force of, say, 1 ton per square foot, would exert a pressure of 2·9 tons.

Now compare this with a block of concrete weighing 1 ton, which would contain about 16 cubic feet, and be represented by a cube one side of which would have an area of, approximately, 6$\frac{1}{3}$ square feet. Such a block, immersed in sea-water, would weigh only 1214 lbs., and a wave striking the face of it with a force of 1 ton per square foot, as before, would exert a pressure of 6$\frac{1}{3}$ tons.

Thus, although the two blocks weigh the same *in the air*, the one possessing high specific gravity has an *effective* weight of 1920 lbs. to resist a wave-stroke of 2·9 tons, whereas the one of low specific gravity has an effective weight of only 1214 lbs. to resist a wave-stroke of 6$\frac{1}{3}$ tons.

The following is a list of some of the stones in common use, with their relative weights:—

Name of stone.	Weight of a cubic foot in pounds.	Name of stone.	Weight of a cubic foot in pounds.
BASALTIC ROCK—		GRANITE AND SYENITE—	
Scotch	184	Aberdeen, grey	165
Greenstone	181	Peterhead, red	165
Welsh	172	Cornish	166
		Mount Sorrel	167
CHALK ...	from 115 to 170	Guernsey	185

Name of stone.	Weight of a cubic foot in pounds.
Limestone—	
Mountain	170
Plymouth	167
Lias	156
Magnesian	151
Oolite—	
Portland stone—Best bed	145
,, ,, Top bed	136
,, ,, Roach bed	127
Bath stone	123
Sandstone—	
Caithness	165
Bramley Fall	156
Craigleith	150
Derby grit	150
Slate—	
Welsh	180
Cornish	158
Shale	165
Porphyry—	
Green	180
Red	175
Quartz	166

Basalt and kindred rocks, in consequence of their high specific gravity and great hardness, are very suitable for use in forming the rubble-mound bases of breakwaters, and in other situations where dressing is not required. However, some descriptions of basalt, which is only a variety of trap-rock, disintegrate rapidly when exposed to the weather, so care is required in making a selection.

The several descriptions of granite and syenite are by far the most useful, and best adapted for general harbour work. These have a fairly high specific gravity, and are sufficiently hard to offer substantial resistance to erosion and rough usage. They can, at the same time, be readily cut and dressed, and, for the most part, they weather well, and are obtainable in large masses.

Speaking generally, granites are distinguished from syenites by the presence of mica, which in the latter is replaced by hornblend. It would, however, be difficult, if not impossible, to draw hard and fast lines between granites, syenites, and porphyries, as they merge imperceptibly into each other, not only as regards their mineral constituents, but also in colour and in the arrangement of their crystals. Thus we have porphyritic granites, syenitic or hornblendic granites, and so forth.

Granites decay chiefly by the decomposition of the felspar which they contain, and also by the mica absorbing moisture, which renders it liable to disintegration by frost.

The yellow or brown appearance which syenites or granites exhibit during decomposition is due chiefly to the oxidation of the iron which they contain.

Felspar crystals vary much in colour, but they may be readily distinguished from quartz by their opacity, and by the fact of their being soft enough to admit of being easily scratched by the point of a knife.

The fracture of good granite should show a fresh-looking, bright, compact surface. A yellowish shade in grey granites, a brown appearance in pink granites, or a dull fracture in either, are pretty sure indications of decay.

Chalk is not suitable for sea-works, unless, possibly, some of the harder kinds, which may sometimes be employed with advantage in positions where they will not be subjected to erosion. Most chalks, however, are liable to become soft under the influence of sea-water, and the amount of wear which chalk cliffs within reach of the sea usually display should be taken as a warning against placing much faith in such a material.

Many of the limestones, oolites, and sandstones are very suitable for breakwater construction, preference being given to the hardest and heaviest of them. They are, however, all—but especially the two first named—subject to the attacks of the *Pholas dactylus*, which is a boring mollusc. Stones attacked by these shellfish are often completely honeycombed by the holes which they bore. The limestone used in the construction of Plymouth breakwater has suffered greatly from them, necessitating renewal in some places.

Another small mollusc (*Saxicava*) is a stone-borer, but is less formidable than the Pholas.

Quartzite, or metamorphic sandstone, is a very hard and durable rock, well adapted for sea-works. The Holyhead breakwater is almost entirely constructed of it. It is generally obtainable in large masses, but it is so hard as to render working it almost impossible. It, like other stones, however, requires to be selected.

In a quarry of this stone which I worked for some years, seams occasionally occurred which were permeated by fine white clay; and although the stone generally was exceedingly hard, that obtained from these seams was friable and unfit for use in exposed situations.

It is well, as far as possible, to ascertain the weathering qualities of stones by noting the condition of exposed faces in old quarry workings, buildings, etc. As a rule, those stones which absorb least water are the best.

Slag from iron-furnaces can scarcely be regarded as a stone—certainly not as a natural one—but it may, perhaps, be as well to notice it here as elsewhere.

In the year 1857 it was proposed by Mr. J. Dunning to use blocks of slag from iron-furnaces of the Cleveland district, to form a very large breakwater (about 5 miles in length) at the mouth of the river Tees. It was intended to cast blocks weighing about 20 tons each, and to throw them into the sea *pierre perdue.*[1]

This proposal, so far as it had reference to the utilization of slag, has since been successfully carried out in the construction of the Tees breakwaters. The blocks used were, however, not so large as those proposed by Mr. Dunning, their weight having been only about 3 tons each.

It was found necessary to protect the seaward face of these slag mounds by a wall of Portland cement concrete, as the slag blocks, when unprotected, were broken up and moved by the force of the waves. Many of the blocks were thrown into the water while hot, which would, no doubt, cause them to crack.

The specific gravity of Cleveland slag is 2·76, that of hæmatite slag 2·84, representing a weight per cubic foot of 172 lbs. and 177 lbs. respectively. They, therefore, in respect of specific gravity, rank before most of the granites and syenites.

The Carron Iron Company state that the specific gravity of their furnace slag is even higher, viz. 3·018, representing a weight of 188 lbs. per cubic foot.

SECTION III.—CONCRETE.

Early use of concrete—Value of concrete in sea-works—Hydraulic lime—Proportion of ingredients in concrete—Mixing by hand—Mixing by machines—Concrete-block making—Roman-cement concrete—Medina cement—Stone-faced blocks—Blocks built of rubble in cement mortar.

Although concrete was used by the Romans and Carthaginians in ancient times in the construction of sea-works, it seems to have fallen into disuse for a long period.

It is only within the last fifty or sixty years that it has again come prominently forward, and its great value in harbour construction been fully recognized.

Its adoption for sea-works during recent years, together with the great advance which has been made in mechanical appliances for dealing with heavy loads at long radii, has quite revolutionized the system of breakwater construction, by rendering it possible to build heavy blocks on shore, and set them in place after they have become hard enough to resist the action of the sea. Large bags, containing concrete in a soft state, can also now be deposited with the greatest ease.

---

[1] "Minutes Select Committee on Harbours of Refuge, 1857," p. 233.

Hydraulic Lime in Sea-works.—English engineers seem to have little faith in lime for sea-works, seeing that, almost without exception, they now employ Portland cement. French, Italian, and some other engineers, on the other hand, still use lime rendered hydraulic by the addition of substances in which silicate of alumina predominates, such as puzzuolana.

As bearing upon this subject, I may mention the following facts which have come under my notice.

The masonry of the superstructure of the Holyhead breakwater was set in lias lime mortar, with which, in some portions of the work, puzzuolana was incorporated.

In course of time the sea removed nearly all the mortar from the joints and beds of the masonry for a considerable distance in from the face of the work. The seaward face, as it is natural to suppose, was affected most; nevertheless, it was necessary to rake out the joints on all the exposed surfaces of the work—including those on the harbour side, which were exposed to the small waves coming across the bay—and to fill and repoint them with Portland cement mortar.

On the sea face of the superstructure holes of considerable dimensions were formed in the masonry, through stones becoming loosened by the abstraction of the mortar. These were discovered and stopped in time, otherwise they would, no doubt, soon have increased in size and endangered the work.

Lime mortar was therefore a failure in this case, and it was noticed that the addition of puzzuolana, so far from improving it, appeared to have a positively injurious effect.

Notwithstanding this, it must be admitted that French and Italian engineers have been more successful than ourselves in the use of lime in sea-works, seeing that it has been largely employed by them in most of the marine works along the shores of the Mediterranean, and is, indeed, still being extensively used.[1]

---

[1] The exceptionally good quality of Mediterranean limes conduces, no doubt, in a great measure, to the success which attends their use.

In depositing lime concrete for under-water foundations, it is sometimes merely thrown into the water from baskets carried upon the head, timber frames and boarding being used to give it the requisite shape, and to retain it in place till hard.

Although, as has already been said, lime concrete is but little used in this country for sea-works, it is largely employed in dock works, and makes excellent work.

In the Liverpool Docks and London Docks, also at Glasgow, Fleetwood, and many other places, hydraulic limes have been used with marked success.

Proportions of Ingredients for Concrete.—In determining the proportions of the ingredients for concrete, the mass should be looked upon as so much rubble masonry.

It is evident that the strength of the mass will depend upon that of the matrix, or mortar, in which the broken stone or pebbles are embedded. Therefore, if it be decided that concrete shall have the strength of, say, 2 to 1 cement mortar, sand and cement should be mixed in these proportions, and a trial be made to see how much broken stone or shingle can be mixed with it, so as to ensure all the interstices being well filled, and a thoroughly good pasty mass formed. This will vary according to the size of the broken stone or shingle used, and it will also be affected by the incorporation, or otherwise, of large pieces of rubble stone in the mass. If these be introduced, it will be found necessary, in order to ensure their being thoroughly well bedded and surrounded by the concrete—an important point to attend to—to make the concrete more pasty and slightly wetter than if no rubble were incorporated.

Later on I will give the proportions which were adopted for concrete in several sea-works as actually executed.

In the preparation of concrete, great care should be exercised in selecting proper materials. These should be as hard and heavy as possible, and perfectly free from all earthy or soluble matter.

They should be thoroughly mixed *in their dry state,* and again after adding the water, which should be quite clean, and only sufficient to give the concrete a moderately thick pasty and slimy consistency.

It is not easy to determine the exact quantity of water except by trial with the materials in use. Even with the same materials, if exposed to the weather, the quantity of water required will vary much, seeing that in wet weather the materials are already moistened to some extent. The quantity of water should, however, be carefully regulated, because if used in excess the strength of the cement will be impaired, whereas if too little be used the concrete will be porous and liable to injury by the action of the sea-water.

Mixing Concrete by hand.—In mixing concrete by manual labour, the usual course pursued is as follows:—

Upon a smooth timber platform, say 14 to 16 feet square, which is termed a "banker," the dry materials are measured in gauges. These may be described as bottomless boxes, which, when lifted, leave upon the banker the material that has been gauged. This gauging should be done at the end of the banker opposite to that from which the mixed concrete will be delivered. The mixers should then arrange themselves in two rows facing each other. The cement having been evenly distributed over the gravel, or broken stone and sand, as the case may be, the first pair of men pass the material on to the second pair, at the same time giving their shovels a twist so as the better to mix it. It is thus passed on from pair to pair—the water being added, through a rose, between the second and third pair—until it reaches the other end of the banker, by which time all the ingredients should be properly incorporated, and the concrete ready to put into the work.

The materials are usually turned twice in the dry state, and twice after the water has been added, which represents four pairs of mixers; but unless the men are properly trained, and give the necessary twist with their shovels in passing the material on, double that amount of shovelling or handling of the material will not produce good concrete.

Concrete-mixing by Machines.—Various machines have been designed for mixing concrete mechanically. They may be generally divided into two classes, namely, those in which the process is intermittent, and those in which it is continuous.

Of the former, Coode's and Messent's may be cited as examples.

Coode's mixer is composed of an inclined cylinder with an axle, upon which it revolves, passing through it diagonally, and resting upon side frames. There is a door at one or both ends of the cylinder, through which it is charged and the concrete delivered when mixed. The eccentric arrangement of this cylinder upon its axle is such that, when made to rotate, its contents are thrown from side to side and end to end, and thoroughly mixed.

In Messent's machine the mixing-vessel is angular and of a somewhat peculiar shape. When half filled with material, and caused to revolve on its axle, the material, as in Coode's machine, is made to turn over sideways as well as endways, thus ensuring good mixing.

Either of these machines may be geared for hand or steam power as desired.

Hoppers are generally used in charging them, and a small overhead tank supplies the water, and at the same time ensures the correct quantity being given to each charge.

These machines are usually—though not necessarily—constructed to mix half a cubic yard at a time, experience having shown that this quantity is more easily dealt with than larger charges. A machine of this size will mix about 10 cubic yards per hour.

Of the latter type of machines, or continuous mixers, Ridley's, Le Mesurier's, and Carey-Latham's are perhaps the best known. A description of the last named will convey a good general idea of a continuous mixing-machine, so it will not be necessary to further refer to the others.

This machine consists of a horizontal revolving mixing-cylinder, within which are spiral ribs, carried upon radial arms. These ribs revolve at a very much slower rate than the cylinder itself, and from them the concrete material, as it is brought up by the revolving cylinder, is thrown off, sideways and forward, a number of times during its passage through the cylinder, at the outer end of which it is delivered as concrete.

Water is supplied about halfway down the cylinder, by means of a central pipe or hollow shaft, at the end of which is a star-rose. Thus the material is well mixed in the dry state before it reaches the point where the water is added.

The materials are automatically measured, and fed into a hopper at the upper end of the cylinder. The sand and broken stone or gravel are measured and lifted by means of buckets attached to chains—dredger fashion. One set of these buckets—the size and number of which may be made to suit any conditions—supplies the sand, and the other the broken stone or gravel, while the cement is fed into the hopper by means of an endless screw, its quantity being regulated to a nicety by means of an adjustable ratchet arrangement. The water is regulated by means of a screw-cock.

The machine is driven by means of a vertical engine, which, together with its boiler, etc., is mounted upon the same frame and carriage as the mixer, the whole travelling upon an ordinary line of rails, and being self-propelling.

The mixing of concrete by any of the foregoing machines is much more expeditious and perfect than mixing by manual labour, and in large works concrete-mixing machines, of one kind or another, are now almost always employed.

At the Newhaven harbour-works (Sussex), a very large "Carey-Latham" machine was in use, it being capable of mixing and delivering about 300 tons of concrete per hour.

A convenient size of machine for general use is one which is termed a "20-yard mixer," by which is meant one that will mix 20 cubic yards per hour. In practice, however, taking stoppages and hindrances into account, a machine of this size cannot be relied upon to turn out more than from 14 to 16 cubic yards per hour.

Concrete block making.—Concrete blocks are usually cast in moulds formed of 3-inch or 4-inch planking, according to the size of the blocks to be made. The sides of the moulds are so put together that they can be easily taken apart for the purpose of freeing the blocks when sufficiently hard. Moulds for the larger sizes of blocks are generally stayed, either by means of bolts passing completely through them, or by horizontal side-stiffening ribs. Where bolts are used, they should be turned the day after the concrete has been put in, so as to facilitate their withdrawal, which should take place at the time of the removal of the moulds—say three to four days after the blocks have been made.

Sometimes pipes are placed in the blocks, through which the stay-bolts or small chains are passed. I, however, much prefer making the sides of the boxes so stiff that the use of through-stays is altogether obviated.

The holes for the T-headed bars, which are commonly used for lifting the blocks (Fig. 71, p. 254), are best made by means of long tapered folding wedges, or "cores," which are easily withdrawn after the concrete has set. At the bottom of these holes chambers are formed of sufficient size to admit of the T-ends of the lifting-bars being freely turned. These chambers are most conveniently formed either by means of cast-iron tapered core-boxes, which leave the blocks when lifted, or by rough wooden boxes, which are allowed to remain in the blocks. Upon the top of these boxes—whichever kind may be adopted—pieces of evenly and finely dressed hard stone, hard wood, or other unyielding material are placed and built into the blocks, for the T-heads to take their bearing upon.

In order to ensure the sides of the moulds leaving the concrete freely and cleanly, they should be painted over with a mixture of boiled soap and water, of the consistency of a jelly.

The floor upon which the blocks are made is usually coated with fine sifted sand.

Blocks should be allowed ample time to harden before being lifted or the moulds removed, otherwise they are apt to become strained, and to develop incipient cracks. Under ordinary conditions the moulds may be removed on the fourth day; and the blocks may be lifted and stacked when from three weeks to a month old. The exact period will, however, depend much upon the proportion and setting properties of the cement which they contain, and also upon the state of the weather. In warm weather they will be found to harden much more quickly than in cold.

The following information respecting concrete in its various forms, as used in the construction of several important works, may be found useful.

The proportions adopted for concrete blocks used in making the breakwaters, or moles, at Marseilles were—

2 parts hard broken limestone.
1 part mortar, composed of 3 parts Theil lime, 5 parts sand.

These were all mixed and formed into concrete by cylindrical mixing-machines.

The moulds were taken off the blocks after a lapse of not less than three days. The blocks for *pierre perdue* work were allowed at least three months to harden before being put into the work, those for use in foundation work being allowed six months.

These blocks are said to have stood well, having been but little affected by the action of the waves, whereas some of those used in constructing breakwaters at other Mediterranean ports—Algiers and Leghorn, for example—are said not to have behaved quite so satisfactorily.

In the breakwater at Algiers, the proportions used for blocks made on shore were—

1 part lime, in paste.
1 „ puzzuolana.
1 „ sand.
3 parts broken stone.

Where concrete was deposited *en masse*, the proportions adopted were—

1 part rich lime, in paste.
2 parts puzzuolana.
4 „ broken stone.

The blocks are said to have set sufficiently hard in twenty-four hours to resist the shock of heavy seas.

In addition to the breakwaters at Marseilles and Algiers, lime concrete was used in those at Alexandria, Cette, and other places.

Blocks for sea-works in Italy are now commonly made of 1 part of lime mortar, 2 of puzzuolana, and 6 of broken stone, hydraulic lime being seldom used, and cement very rarely. For facing-blocks the proportions generally adopted are 1 of lime, 2 of puzzuolana, and 4 of broken stone (*Min. Proc. International Maritime Congress,* 1893).

The concrete blocks used in constructing the Ymuiden breakwaters (Holland) were composed as follows:—

FACE BLOCKS.

1 part Portland cement.
3 parts sand.
5 „ shingle.

HEARTING BLOCKS.

1 part Portland cement.
4 parts sand.
5 „ broken bricks.

No blocks were used *above* low water until after a lapse of two months in summer and three months in winter from the time of their manufacture. No blocks were used *below* low water until they were three months old.

These blocks have not stood the rough usage to which they have been subjected quite so well as could have been wished. They were, however, made under exceptional difficulties, neither stone, shingle, or sand of good quality being obtainable in the district.

The proportions of Portland-cement concrete used in making the blocks for the south breakwater at Aberdeen were—

1 part Portland cement.
4 parts sand.
5 „ gravel.

Large pieces of rubble stone were also incorporated.

For the Colombo breakwater the proportions used were—

1 part Portland cement.
2 parts sand.
6 „ broken stone.

The moulds were removed from these blocks after a lapse of three days. Blocks were lifted and stacked when three and a half weeks old, and they were set in the work when six weeks old.

At Newhaven (Sussex), the proportions used in the concrete for bag-work and mass-work, of which the breakwater is entirely composed, were the same, viz.—

1 part Portland cement.
2 parts sand.
5 „ shingle.

At Fraserburgh, the proportions first adopted for bag-work were—

1 part Portland cement.
7 parts sand and gravel.

But as the current increased with the extension of the breakwater, it was found necessary to reduce the proportion of sand and gravel to 4½.

The proportions used for mass-work during fine summer weather were—

1 part Portland cement.
9 parts sand and gravel.

During more stormy weather, the proportions used were—

1 part Portland cement.
7 parts sand and gravel.

At each of the harbours of Portsoy and Sandhaven, the proportions used in the piers were—

1 part Portland cement.
6 parts sand and gravel.

In the paper on these harbours, which the late Mr. Willet read before the Institution of Civil Engineers, he stated—

"I am convinced, from recent experience, that the proportion of 1 of cement to 9 of gravel and sand, adopted at Fraserburgh, is too weak for such exposed works. The proportion adopted for Sandhaven and Portsoy, of 1 part of cement to 6 parts of gravel and sand, has been proved to form concrete of more suitable strength. All the plans hitherto tried along the north-east coast of Scotland, for concrete-work below low water, have been more or less inadequate to withstand the strains to which they are subjected during heavy gales."[1]

For the Kustenjie breakwater the blocks were composed of—

1 part of Portland cement.
2½ parts clean, sharp sand.
5½ „ broken stone.

When, as was sometimes the case, it was necessary to use sand of inferior quality, the proportion of cement was slightly increased.

These blocks were sometimes placed in the work when only twelve to fourteen days old. This is, however, in my opinion, not a prudent course to adopt—at all events if weight, in the shape of additional blocks or otherwise, is to be shortly placed upon them.

Blocks, when stacked in a block-yard too "green," notwithstanding that the greatest care may be taken, are often found broken when they are again lifted. The same may happen to them when placed in the work, without the fact being known, and trouble or failure may result therefrom.

In all the foregoing examples proportions were by measure, not by weight.

Concrete made with Roman Cement may often be employed with advantage in exposed situations, where the wash of the sea would render the use of Portland cement difficult. Owing to its greasy nature and quick-setting properties, work in which it has been used will resist the action of the water, even if it should come over it within, say, ten to fifteen minutes of its being deposited. It should be mixed only as required, and be put into the work without delay.

Medina Cement has much the same properties as Roman cement, but its nature is even more greasy. When fresh, it sets a few minutes after mixing; and it will withstand the wash of the sea almost immediately after mixing, and while yet soft. It is exceedingly useful for pointing joints, and for other purposes in tide work, also for protecting Portland cement until it is hard enough to take care of itself.

---

[1] *Min. Proc. Inst. C.E.*, vol. lxxxvii. p. 131.

Mr. Messent, M. Inst. C.E., engineer to the River Tyne Commissioners, has kindly furnished me with the following particulars respecting the use of Roman cement in the Tyne piers and elsewhere :—

"Throughout the pier work I have been in the habit of using Roman cement mortar in the walls up to about high water, and, except in the very finest weather, the Roman cement concrete hearting is taken up nearly as high, but this depends greatly upon the weather.

"The strength of the composition of the materials also varies according to the season and exposure.

"For ordinary work, exposed to a wash immediately after setting, the proportions I have used are 1 cement, 1 sand, and 2 gravel, with as many largish stones or 'displacers' as can be got in and separated; but towards the end of the season, in any very exposed places, I nearly double the quantity of cement.

"I have recently constructed a small breakwater at Cullercoats entirely of Roman cement concrete rubble.

"I have also recommended the protection of the outer breakwater at Scarborough by an apron similarly composed, which, although the work was commenced in August last (1890) and finished at the end of November, and has since been exposed to very heavy storms, has not suffered in any way.

"As to the strength of Roman cement, if it were finely ground I dare say it would not be very much inferior to that of Portland cement; but I never use it with more than an equal proportion of sand, and frequently, in exposed places, with less."

In order to protect concrete blocks from erosion, they are often faced with hard stone. This is of great importance where the face is likely to be exposed to the action of rubble or shingle driven and rolled about by the sea (see p. 106).

Well-built blocks of hard rubble in cement are stronger, and better able to resist wear, than those made of concrete; but they are more costly, and cannot be made so quickly.

SECTION IV.—CEMENTS.

Portland cement—Analyses of clay and chalk—Process of making Portland cement—Air-slaking—Porosity in concrete—Indications of good Portland cement—Rate at which Portland cement briquettes gain strength with age—Apparent decrease of strength at age of seven or eight months—Analysis of good Portland cement—Roman cement—Medina cement.

The very existence of a sea-work may depend upon the quality and manipulation of the cement used in its construction; so it is necessary that those engaged upon such works should have a thorough knowledge of the subject.

Portland Cement, which is much more largely employed in harbour construction than any other, is generally made by intimately mixing and calcining together clay and chalk; but, seeing that clays and chalks vary greatly in their composition, the proper proportions can only be determined by careful analysis.

Mr. H. K. Bamber, whose large experience in such matters is well known, gives the average composition of a good clay and of a good average soft chalk, suitable for the manufacture of Portland cement, as follows:—[1]

CLAY.

Silica	54·84
Alumina and oxide of iron	25·08
Lime	0·90
Magnesia	0·80
Carbonic acid	0·83
Sulphuric acid	1·20
Organic matter and moisture	16·35
	100·00

CHALK.

Silica	1·15
Alumina and oxide of iron	0·78
Lime	54·00
Magnesia	0·25
Carbonic acid	42·50
Organic matter, etc.	1·32
	100·00

Although clays and chalks similar to the above are doubtless very suitable for the manufacture of Portland cement, others of very different composition are frequently used, and it is only by making constant chemical tests, especially during the process of mechanically mixing or blending together the chalk, clay, and water in the washing-mills, that the right proportions can be ensured.

---

[1] *Min. Proc. Inst. C.E.*, vol. cvii.

Mr. Bamber's description of the process of Portland cement manufacture is so clear and concise, that I cannot do better than give it in his own words, as follows :—

> "In the older works the mixture of clay, chalk, and water obtained in the washing-mills is run into "backs,"[1] and allowed to settle. The water is then drawn off, and the solidified mixture carried to drying-plates, to remove the greater part of the remaining moisture. These drying-plates are heated by coal or coke, and in some cases are so arranged that the waste heat of coking-ovens is used for the purpose.
>
> "In more recently erected works, the slurry is only mixed with sufficient water to enable it to run along the troughs that conduct it to the horizontal flues in direct communication with the interior of the kilns. All the heat that passes from the kilns during the burning of the cement is thus carried over the slurry, which is dried rapidly and cheaply. These flues also being part of the kilns themselves, less labour is required in packing the kilns with the dried slurry and coal or coke. In either case, when the slurry has been sufficiently dried, it is carefully packed into the kilns with the proper mixture of coal or coke. The quality of the resulting cement depends to a great extent on the careful performance of this part of the process; for if the clay and chalk mixture be added in too large lumps, the outside only will be properly clinkered, while the interior will remain an imperfectly burned powder; whereas *thorough clinkering is absolutely necessary in order to obtain good cement.*
>
> "The first effect of the heat on the mixture in the kilns is to drive off water and carbonic acid, thereby converting the chalk into quicklime, which decomposes the clay, combining chemically with both the silica and alumina, forming calcium silicate and calcium aluminate, of which properly burned cement chiefly consists.
>
> "Clinkering is a state of semi-fusion, and it is requisite that this should take place in the kilns, so that when they are emptied there should be only good clinkers without dust. It is on this process that the production of strong cement depends, for it is at the time of this semi-fusion that the chief chemical action takes place. In the clay, which is mainly a silicate of alumina, the silica and alumina are in intimate chemical combination, the silica acting the part of an acid, and the alumina that of a base. Alumina, however, has also the

---

[1] Settling-ponds or reservoirs.

UNIVERSITY OF TORONTO
DEPARTMENT OF CIVIL ENGINEERING
Municipal and Structural

power, under certain circumstances, of taking the place of an acid, and this occurs during the semi-fusion in the kiln; the lime decomposes the clay, and combines both with the silica and alumina, forming calcium silicate and calcium aluminate, which, when finely ground, constitute good cement. When mixed with water, the cement combines chemically with a certain quantity, and crystallizes into a solid block, impervious to water. In the case of concrete where sharp sand is used, some of the lime gradually combines chemically with it, forming an additional quantity of silicate of lime, and this still further improves the strength of concrete. During the process of absorption of water and crystallization, the whole should be kept as much at rest as possible, for excess of water, especially in motion, would separate the fine particles, and weaken the concrete, and form an incrustation of white chalk, etc.

"In order to know whether cement obtained from any manufacturer is good, a complete chemical analysis is requisite, in the first place, to show if it has the right composition. This will, however, only give the proportions in which the ingredients exist, which may be exactly the same in a well-clinkered cement as in one that has only been burned enough to drive off the water and carbonic acid without causing any further chemical action between the several ingredients. The usual test of proper burning is the weight of a striked bushel of the cement, which is required to be not less than 112 pounds to 115 pounds. This is a very uncertain test, as many little points during the filling of the mixture may make several pounds difference in the weight. A much more reliable test is the specific gravity, which should accompany the analysis. A properly clinkered and ground cement, when new, will have a specific gravity of 3·1 to 3·15. If it is as low as 2·9, or less, it shows that the cement has not been properly burned. Thus the chemical analysis gives the actual composition of the cement, and the specific gravity gives the density, which cannot be brought up to 3·1 unless the ingredients have been thoroughly and properly clinkered."

In what is termed the "dry process" of making Portland cement, the ingredients, instead of being mixed together with water and run into settling-ponds or "backs," are thoroughly dried and reduced to powder. This powder, in which the proportions of clay and lime are carefully adjusted, is then moistened and formed into bricks, which are dried, calcined, and ground into cement in precisely the same way as the slurry is treated in the wet process.

The next thing to be considered is the fineness to which cement should be ground, and on this point opinions differ considerably. Apart from pecuniary considerations, however, there can be little doubt that the finer it is ground the better.

Cement "core"[1] has sometimes been collected and mixed with water without its exhibiting any setting qualities or any inclination to slake. It has, therefore, been erroneously considered inert, and looked upon as so much sand.

Hard-burnt clinkers of lime, when treated singly, are often very difficult to slake; but when associated in a heap with less refractory lumps, and there brought under the influence of the general heat and moisture of the mass, they ultimately yield. So it is with the core in cement, or at least with a large percentage of it, which therefore tends to disintegrate work in which it may have been used. The finer particles of cement absorb water and set more quickly than the coarser ones; but the latter continue to absorb water, though sometimes very slowly, and in doing so they expand and break up the mass in exactly the same way that small particles of unslaked lime would do; in fact, it is the free or caustic lime in the cement which causes this expansion to take place. The core ought not, therefore, to be disregarded, but, on the contrary, it should be looked upon as an element of danger.

By thoroughly air-slaking cement before using it, until no tendency to expand remains, the dangerous properties of the core will to a great extent be removed, and the cement generally will be rendered safer for use.

In the process of air-slaking cement increases considerably in bulk, which indicates how necessary it is that it should be subjected to this treatment; it also loses weight, becomes slower in setting, and, in short-time tests of strength, it gives lower results than when it was fresh. In the course of a few months, however, the strength of briquettes made with slaked cement will often be found to have overtaken that of briquettes made with the cement when fresh.

I make it a practice not to use Portland cement until a briquette of the same, seven days old, will stand being boiled in water for six consecutive hours without turning soft or showing indications of swelling. A good cement air-slaked until it will stand this test may be used with confidence, because it can never swell in the work; and if concrete made with it be properly

[1] The coarse particles of cement which will not pass through the testing-sieve.

proportioned and mixed—a sufficient quantity of water being used to ensure its not being porous—it will not go to pieces or give any cause for anxiety when put into the sea.

I am aware that, in the opinion of some, cement cooled to the extent just described would be considered spoilt; but I am guided by experience, and I am convinced that a very large proportion of the trouble which is experienced with concrete structures in the sea is attributable to the use of unslaked cement. When once concrete becomes porous, whether by expansion caused by hydration or otherwise, the sea-water, gaining admission, takes up the lime, deposits magnesia, and thus renders the work rotten and honeycombed.

A good Portland cement for sea-works should fulfil the following conditions:—

(1) It should be of a uniform dark grey colour.

(2) Its specific gravity should not be less than 3·14 when fresh, or 3·125 a month after being ground. (The weight-per-bushel test may be disregarded as misleading and useless.)

(3) It should be finely ground, at least 92 per cent. by weight, passing a sieve with 2,500 meshes per square inch, and the whole passing a sieve with 1,600 meshes per square inch, the sieves being made of wire No. 37 B.W.G. (= ·007 inch).

(4) The time of setting should be from half an hour to an hour and a half, when the temperature of the air is about 60° Fahr. and the cement fresh.

Warmth hastens the setting of cement, while cold retards it.

In making briquettes for testing, the cement should be mixed with sufficient water to form a tough paste, such as will fill the moulds without ramming.

(5) Pats or slabs, $\frac{1}{4}$ inch in thickness, after remaining in water for twenty-four hours, on being heated to a temperature of 160° Fahr., should not show any signs of "flying."

(6) Briquettes, with a minimum section of $1\frac{1}{2}'' \times 1\frac{1}{2}''$, made with the cement when fresh, should stand the following tensile strains:—

	lbs.		lbs.
Briquette 2 days old, from	450	to	600
„ 4 „ „	700	„	900
„ 7 „ „	950	„	1100

The briquettes, twenty-four hours after mixing, should be placed in water, and they should be kept there until required for testing.

The following diagram (Fig. 20) gives a fair idea of the manner in which air-slaked Portland cement gains strength with age. It will be seen that after the lapse of seven or eight months from the time of mixing, it nearly attains its maximum strength, the gain after that period being very small. Indeed, when seven or eight months old briquettes often show a slight falling off in strength, as indicated by the dotted line.

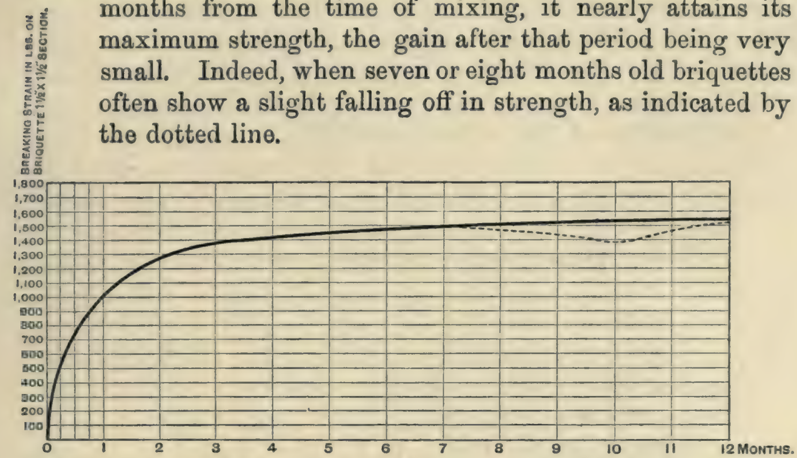


FIG. 20.—Diagram showing, approximately, the rate at which briquettes of Portland cement (aërated) gain tensile strength with age.

It has been suggested, in explanation of this phenomenon, that, seven or eight months after mixing, the elasticity of Portland cement begins to diminish by reason of continued crystallization producing brittleness; but this explanation is not altogether satisfactory, seeing that after this diminution in strength has been observed the briquettes often gradually gain strength again. In briquettes made with "hot" cement, it is probable that this loss of strength—which is often very marked and continuous—is attributable to gradual expansion and disintegration.

The following may be taken as a fair average analysis of a good Portland cement:—

Silica	21·8
Alumina and oxide of iron	12·0
Lime	61·3
Magnesia	1·1
Sulphuric acid	1·1
Carbonic acid	0·9
Potash and soda	0·9
Insoluble residue (sand, etc.)	0·9
	100·0

Only the first three constituents are essential to good cement, but the presence of the others is generally unavoidable.

A slow-setting cement, unless the slowness be due to age and aëration, indicates an excess of lime, and is therefore unsafe for use.

Roman Cement is manufactured from septaria nodules of the London clay formation, found in the Isle of Sheppey and elsewhere. The stone is broken into small pieces, and calcined in kilns in much the same way as Portland cement, but at a somewhat lower temperature. It is then ground into a fine powder.

The colour of the calcined stone is generally a rich brown, but this depends much upon the percentage of oxide of iron which it contains, and is no indication of quality.

The composition of the stones from various districts varies considerably. The Sheppey stone usually contains about 55 parts of lime, 38 of clay, and 7 of iron; while Yorkshire stone contains as much as 62 per cent. of lime, and Harwich stone as little as 49 per cent. The natural stones have a fine close grain, pasty appearance, and greasy surface when broken.

Unlike Portland cement, the best Roman cement is that which is the lightest. It should be ground very fine, and its weight per cubic foot when freshly ground should not exceed 60 lbs.[1] It should set very quickly after being gauged—say in about fifteen minutes.

It is chiefly used in sea-works for temporarily pointing or protecting new work, but it is sometimes employed for making concrete and for setting masonry in situations where the work is much exposed. It is more costly than Portland cement, and never attains the same strength. Moreover, what strength it possesses is quickly reduced if sand be mixed with it, as will be seen from the following table:—

TENSILE STRENGTH PER SQUARE INCH OF SECTION.

	Roman cement (neat).	Roman cement 1 part, sand 1 part.	Roman cement 1 part, sand 2 parts.
	lbs.	lbs.	lbs.
Seven days after mixing ...	71	20	3
Fourteen days " ...	75	29	18
One month " ...	135	35	27

---

[1] The specific gravity of Roman cement varies more than that of Portland cement, but may be taken at from 2·50 to 3·00.

Roman cement soon loses its setting properties when exposed to the air; it should therefore be kept in the casks in which it is supplied, and in a dry place, until required for use. Owing to the rapidity with which it sets, only small quantities should be gauged as required for immediate use.

Medina Cement has already been referred to (p. 122). It is of a light yellow-brown colour, and is made from septaria found in Hampshire and in the Isle of Wight. In its properties and uses it much resembles ordinary Roman cement.

The three cements which have now been described, namely, Portland, Roman, and Medina, are those commonly used in harbour-works; there are, however, some others which are occasionally used, but it is not necessary to further refer to them here. Full information respecting them may be found on reference to "Notes on Building Construction," Part III. (Longmans & Co.), or to "Limes, Cement, etc." (Lockwood & Co.).

The use of lime and puzzuolana in sea-works, as commonly adopted by French and Italian engineers, was noticed when treating of concrete, in Section III. of this chapter.

SECTION V.—TIMBER.

Various kinds of timber used in sea-works—Destruction of timber by sea-worms, etc. —*Teredo navalis*—*Limnoria terebrans*—*Chèlura terebrans*—Methods of preserving timber—Greenheart, sneezewood, and jarrah repel sea-worms—Creosoted Baltic red-wood, oak, and teak useful in some localities—Pitch pine quickly attacked by sea-worms—Greenheart and jarrah liable to split—American rock elm useful for fendering—Black ironwood eaten freely by *Teredo navalis*.

The different kinds of timber which are more or less commonly used in sea-works are as follows:—

Baltic red-wood (*Pinus sylvestris*).
Pitch pine (*Pinus rigida*).
Oregon pine (*Abies Douglaisi*).
English oak (*Quercus robur*).
American oak (*Quercus alba*).
Teak (*Tectona grandis*).
Greenheart (*Nectandra rodiœi*).
Jarrah (*Eucalyptus marginata*).
American rock elm (*Ulmos racemosa*).

In addition to these, black ironwood (*Olea laurifolia*) and sneeze-wood (*Ptæroxylon utile*) have been largely used in Cape Colony.

All of these woods are, in a greater or less degree, subject to attack from marine animals—commonly spoken of as "sea-worms"—and their value for use in marine works depends greatly upon their power to resist injury or destruction by them.

The family of Pholadidæ may perhaps be considered the worst enemies of timber structures in the sea; but the attacks of their smaller relatives, *Limnoria terebrans* and *Chèlura terebrans*, are by no means to be despised, as will hereafter appear.

Of the Pholadidæ, *Pholas dactylus*, although pre-eminently a rock-borer, is often found in timber. It is, however, the *Teredo navalis*, or common shipworm, of the same family, which most frequently assails and is most destructive to timber structures in the sea.

These molluscs resemble worms, and they bore into the hardest kinds of timber with apparently as much ease as they do into the softer kinds.

I have found *Teredo navalis* in the byssus or fibre of mussels, on detaching bunches of them from concrete blocks, but I could not perceive any indication of an attempt having been made to perforate the concrete itself.

Usually, soon after entering timber, these worms alter the direction of their bore-holes until it corresponds with that of the grain of the wood. These galleries, which are sometimes of great length, are lined throughout with a hard, smooth, but very thin shell; and it is curious to see how, notwithstanding that a pile may be completely riddled with them, they steer clear of each other, although often approaching so close that not $\frac{1}{16}$ inch of timber divides them.

Attempts have been made to explain how these worms can bore into timber, by suggesting that they destroy or soften the wood by secreting acids, or that they wear it away by the continuous action of a water-jet, or by a rasping process caused by a movement of the head, and so forth.

If any one will take hold of one of these worms just behind the head, pinching it firmly and compressing the back of the head, such treatment—which requires considerable pressure, and, I fear, is not very pleasant to the worm—will cause two strong, sharp, black teeth to protrude, of such hardness that the blade of a penknife can make no impression upon them. I feel quite sure that, after an inspection of these, it will be readily conceded that the animal is perfectly well able to bore away to its heart's content, without having to resort to the secretion of acid or to any other aid.

I have never heard any question raised as to how the larvæ of the goat moth (*Cossus Ligniperda*), leopard moth (*Zeuzera Æsculi*), or those of the "Clearwing" family and other wood-eating insects, eat into the solid heart timber of elms, oaks, poplars, etc., and I am unable to understand why the *Teredo* should not be credited with similar powers.

The *T. navalis* attains a length of 18 inches to 2 feet, and bores holes up to ¾ inch in diameter. It usually grows to a larger size in warm latitudes than in the colder ones; but I have seen timber as far north as Thurso (58° 36′ N. Lat.) riddled with *Teredo* holes, some of which I could put my finger into. The holes do not, however, usually exceed ⅜ to ½ inch in diameter, and the worms commonly found are not more than from 6 to 8 inches long.

There is a very large species of *Teredo* (*T. gigantea*) which inhabits the East Indian and China seas. It is said to attain a length of nearly 6 feet, and to measure 3 inches in diameter at its thickest part. It seems chiefly to inhabit shallow water, amongst mangrove trees, and is not so much to be feared as the smaller species.

Although the *Teredo* attacks submerged timber at all moderate depths, it, like the other timber pests, is most active between low water of spring tides and high water of neaps.

I have already mentioned *Limnoria terebrans* and *Chèlura terebrans.* These are small crustaceans, scarcely less formidable than the *Teredo.* They are akin to, and somewhat resemble respectively, small wood-lice and sandhoppers. They do not measure more than from $\frac{3}{16}$ to ¼ of an inch in length.

I have seen piles of pitch pine so perforated by them that large pieces, almost resembling sponge, and easily crushed by the hand, could readily be detached.

They appear to work chiefly in the cellular tissues of the wood, and therefore generally attack the ends of timbers first; but the harder woody fibre is by no means proof against them. Both they and the *Teredo* seem to be very fond of getting into timber through joints and bolt-holes.

Various methods have been adopted for protecting timber from the ravages of these marine marauders.

Covering with copper sheathing has been tried, but with only partial success, as the worms, when young, are so small that they can penetrate between the joints of the copper, and so find access to the wood. It is, moreover, rather a costly expedient, and liable to cause rapid decay of any submerged iron that may be about the structure.

Studding the surface of timber with large-headed iron nails, driven close to each other, appears to answer fairly well. These rust and form a casing of iron oxide, which repels the attacks of the *Teredo*, etc. This is, however, also an expensive process, and it somewhat reduces the strength of timber.

Some timbers, in their natural state, resist the attacks of sea-worms much better than others. This is not in any way due to their texture, but to the fact that they contain poison or pungent oils which are distasteful to these creatures. Of these greenheart, sneezewood, and jarrah are the best, teak and oak being also fairly good.

In many situations, well-creosoted Baltic red-wood timber, containing at least 10 lbs. to 12 lbs. of creosote per cubic foot, will be found to answer fairly well.[1]

A few years ago (1889), I happened to visit Holyhead during the time that some of the piles of the old harbour timber jetties were being renewed. Those which were being taken out were of creosoted timber, and they had been in the jetty since the year 1860, or for about twenty-nine years. Some of them were certainly very badly eaten, apparently entirely by *Limnoriæ*, but the timber which remained was perfectly sound.

As the cost of creosoted timber does not usually much exceed one-third that of greenheart, it is well worth while to consider whether, in positions where the worm is not very active, it may not with advantage be used. This point, like many others, resolves itself into a question of expediency.

In order to arrive at a correct decision, it is necessary that reliable data should be forthcoming respecting the site where it is intended to use the timber; otherwise the estimated life of the timber may be very wide of the mark.

---

[1] It is customary with French engineers, and some others, to use as much as 18 lbs. or 19 lbs. of creosote per cubic foot of timber, when such is to be used in sea-works.

So far as I am aware, the only satisfactory information on this subject is that derived from a careful examination of various kinds of timber which may have been in the sea for some considerable time at the site of the proposed works.

It cannot be argued that, because the worm is very bad or does not exist in one place, similar conditions will be found to obtain in another locality, although the two places may be only a mile or two apart.

It would be well if those in charge of harbours or sea-works would experiment with various kinds of timber, and make notes periodically of their condition. By so doing, much useful information might be gained respecting the sea-worms which infest different localities, and the extent to which the various kinds of timber suffer from their attacks.

One word of caution as to the placing of the test-pieces. At Holyhead it was found, in renewing creosoted timber, that the *Limnoriæ* did not attack the new piles so long as old timber remained for them to feed upon; but when this was taken away they were apparently driven to do so by sheer starvation.

Similarly, in Algoa Bay (Cape Colony) I removed a long timber jetty and other structures, in which a variety of woods had been used as piles and bracings. These included creosoted Baltic pine and greenheart. The creosoted timber was badly eaten, both by *Limnoria* and *Teredo*, but the greenheart was untouched, although it had been in the sea for many years.

All the timber structures about the port having been removed, others of iron were substituted. The fenders of these latter were all made of greenheart, of excellent quality. Nevertheless, to the astonishment of everybody—greenheart being generally considered proof against the worm—they were very quickly attacked by the *Teredo*, etc., and in less than seven years so badly were they eaten that in many cases they required renewal.

In view of the foregoing, it would appear desirable to keep experimental pieces of timber of different kinds far apart from each other, otherwise the worms may be attracted to those which they prefer, and leave the others untouched, as was undoubtedly the case in the instances which I have cited.

Baltic Red-wood (creosoted), as has already been pointed out, may with advantage be used in some localities.

It is readily obtainable in logs up to 12 inches or 13 inches

UNIVERSITY OF TORONTO
DEPARTMENT OF CIVIL ENGINEERING
MUNICIPAL AND SANITARY

square and 40 feet in length. It is fairly strong, and is easily worked. After creosoting, the surface of the timber should be disturbed as little as possible, because it contains by far the largest share of the creosote.

Where practicable, all notching and cutting should be done before the timber is creosoted. When this cannot be done, the newly exposed surfaces should be well served with hot creosote, and the joints should be made as close as possible.

I have seen creosoted half-logs—halved after creosoting—used as bracings and walings, destroyed by the worm just as quickly as if they had not been creosoted at all.

Pitch Pine and **Oregon Pine** are valuable chiefly on account of the great length and large scantling of the logs, or masts, which can be obtained. They are generally employed in the construction of staging, and are excellent, strong timbers; but they are quickly attacked by sea-worms. Staging in which they are used ought, therefore, to be carefully examined periodically.

Oak and **Teak** are good timbers for pile-work, and for many other purposes. They are not so freely attacked by the worm as those of the pine family, and in many situations they are very durable. They may be obtained, without difficulty, in logs of from 12 inches to 20 inches square, and from 20 feet to 35 feet in length. English oak is, however, becoming scarce.

Greenheart is the wood, of all others, upon which engineers rely for durability in sea-works. Although it sometimes fails—as has already been pointed out—it is generally proof against sea-worms of all kinds, and in exceptional localities where greenheart will not stand, no other timber will.

It is very strong and tough, but piles are liable to split when being driven. They should, therefore, be afforded temporary support during this operation, by bolting on strong iron bands or cramps, not only near the head, but also at intervals of say 6 or 8 feet throughout their length, as circumstances may indicate. It is much easier to prevent a split than to stop one when once started.

The usual immunity enjoyed by greenheart from the attacks of sea-worms is due to the poisonous oil which it contains. A wound caused by a splinter of this wood almost invariably festers.

Logs from 12 inches to 15 inches square, and up to 40 feet in length, may be easily obtained.

Jarrah.—The quality of this timber is much influenced by the nature of the soil upon which it is grown. The best, and only kind serviceable for sea-works, is that obtained from the summit of the granite and ironstone ranges south of Perth, in Western Australia. That grown upon the sand-flats in the same district is of inferior quality.

The best jarrah effectually resists the attack of sea-worms, and may be obtained in logs of large size, viz. from 40 feet to 45 feet in length, and up to 24 inches square. Round masts may be obtained measuring from 50 feet to 60 feet in length, and from 3 feet to 4 feet diameter at the large end, tapering to 12 inches or 18 inches diameter at the smaller end.

In ordering Jarrah, special care should be taken to ensure only the best description being supplied. In appearance, the good and bad qualities vary but little, and cases of failure have occurred where timber grown on the sand-flats has inadvertently been used.

A serious objection to this wood is its extreme liability to split, not only by exposure, but also while being driven as piles. In driving piles, it is necessary to hoop them in the same manner as greenheart.

This tendency to split is, however, much more pronounced than in greenheart, and, notwithstanding all the precautions which may be taken, piles often split so badly as to necessitate their being drawn and cast aside.

In driving piles of this timber, or of greenheart, a ram weighing not less than 25 cwt. should be used, and a short fall —say 3 feet to 4 feet—should be given.

In jarrah, decay usually commences at the heart.

American Rock Elm is very tough, and is chiefly used for "fendering." It is durable in water if not attacked by sea-worms, which it cannot resist.

Black Ironwood has been extensively used in sea-works in Cape Colony.

It is very hard, tough, and heavy, and possesses great strength. Notwithstanding these qualities the *Teredo* eats it freely, and out of water it is liable to decay somewhat rapidly. It is not, therefore, a very suitable wood for sea-works.

It may be obtained without difficulty in logs of from 12 inches to 14 inches square, and up to 35 feet or 40 feet in length.

Sneezewood is as strong and as hard as black ironwood, and it contains an essential pungent oil, which renders it equally as good as greenheart in resisting the ravages of sea-worms.

I have, nevertheless, on one or two occasions, found *Teredo navalis* in the very heart of it.

Unfortunately, sneezewood trees do not attain a large size, and it is very rare indeed to find a straight one. Hence scarfing becomes necessary if piles of even moderate length and scantling are required, and the structure in which they are used presents an unsightly appearance.

The timber is, nevertheless, a valuable one, and its cultivation well deserves the attention of the Colonial Forestry Departments.

It seems probable that, if the trees were grown in dense forests, and received proper attention when young, they might grow straight and attain a larger size than they do at present.

In exceptional cases, where the sea-worms are very active, it is well, as far as possible, to substitute iron for timber in pile-work, and also for under-water bracings, etc., timber fenders or rubbing-pieces being so arranged that they may be renewed without difficulty.

SECTION VI.—IRON AND STEEL.

Durability in sea-water—Records differ widely—Results of experiments—Effect of galvanic action—Structural and chemical differences affect rate of corrosion—Simple corrosion—Rate of corrosion of plates, etc., of s.s. *Gambia*—Effect of exposure on castings at Bell Rock lighthouse, on wrought-iron rails at Port Elizabeth, on ironwork of piers at Ramsey and Port Elizabeth, and on ironwork of beacon at Wolf Rock—Beardmore on decay of iron—Wrought iron more durable than cast iron in sea-water—Mallet on preservation of iron—Redman on decay of iron—Pier at Milton-on-Thames—Gravesend town pier.

Iron and Steel have not hitherto entered very largely into the designs of breakwaters, but their use in the construction of landing-piers and kindred sea-works is very general.

To describe the numerous varieties of iron and steel, their production, distinctive qualities, uses, strength, and so forth, would occupy too much space in the present work, and would, moreover, be out of place. The subject has been very fully treated in works by Fairbairn, Bloxam, Percy, Matheson, and others, and also in Part III. of "Building Construction" (Longmans & Co.), where, in about eighty pages which are devoted to this subject, a vast amount of useful information has been compressed.

In connection with the employment of these metals in sea-works, a very important factor has to be considered. I refer to their durability, or power to resist the corrosive influences of the saline constituents of the water, aided, as they are, by carbonic acid gas, oxygen, and, under certain circumstances, by galvanic action arising from various causes.

The records of observations made on the corrosion of metals in sea-water, under varied conditions, differ so widely from each other, and indeed appear to be so contradictory the one to the other, that with our present knowledge it seems to be impossible to lay down any rule for the rate of oxidation of metals in sea-water, any more than it can be done for similar metals on land. Nevertheless, records of what has actually taken place—especially if all the surrounding conditions have been carefully noted—enable deductions to be drawn by analogy, and we may hope that, as these records multiply, it may be possible to predict what the life of an iron or steel structure in the sea will be with more accuracy than is possible at present.

In the years 1884 and 1885, Mr. T. Andrews communicated to the Institution of Civil Engineers the results of his careful and valuable investigations—extending over a period of about four and a half years—on galvanic action between wrought iron, cast metals, and various steels during long exposure in sea-water; and also on the simple corrosion of these metals.

In the first series of experiments, the test-bars operated upon, in the galvanic tests, were 13 inches long, accurately turned to exactly 3 inches diameter, and polished. These bars were placed in galvanic connection, and were immersed in jars or baths containing filtered sea-water, which was periodically changed, and compensation made for evaporation by the addition of distilled water.

After 300 days' immersion the bars were accurately gauged by a very delicate gauge, measuring absolutely to $\frac{1}{1000}$ inch; and it was found that the several specimens of steel had lost in diameter, on an average, 0·0022 inch, the cast-metal specimens 0·0077 inch, and the wrought-iron nil, excepting in two specimens, in which the loss amounted to 0·0018 and 0·0010 respectively. The galvanic action going on between these metals was clearly indicated and measured by galvanometers.

For a distance of 3 inches below the water-line all the bars were coated with a reddish-yellow peroxide of iron, from absorption of oxygen; and below this level they were covered with a fine black carbonaceous deposit, which it was considered would develop local galvanic action and cause pitting.[1]

It might appear that small differences in the composition of various irons and steels would not be capable of setting up any appreciable galvanic action when these metals are in contact, or of greatly affecting the rate of their corrosion. The experiments conducted by Mr. Andrews, however, show that such is far from being the case, and that what might be considered quite insignificant chemical or structural differences constitute a very important element of destruction.

The rate of corrosion of various qualities of steel plates, in galvanic connection with wrought iron, was increased, beyond the rate of simple corrosion of similar plates, by about 27 per cent. on the average of the tests made.

In experiments on simple corrosion, bright plates being exposed singly and separately to sea-water for a period of 110 weeks, Mr. Andrews found the loss by oxidation, per square foot of surface exposed, amounted on an average to—

260·82 grains in the wrought-iron plates = $\frac{1}{2271}$ inch in thickness per annum.

313·06 grains in the various kinds of steel plates = $\frac{1}{1892}$ inch in thickness per annum.

385·15 grains in the cast-metal plates = $\frac{1}{1538}$ inch in thickness per annum.[2]

These results do not agree well with measurements which I shall presently give, indicative of the rate of corrosion of wrought-iron plates and bars in the wreck of the s.s. *Gambia.*

This wreck lay in the Indian Ocean, fully exposed, not only to the corrosive, but also to the erosive power of the waves; the water in contact with the plates was therefore being constantly renewed. All the plates and bars that were measured lay between high and low water, and were thus exposed to the combined action of air and water.

These unfavourable conditions would doubtless account for a good deal of the difference to which I have referred, but it is, nevertheless, so large as to be rather startling.

[1] *Min. Proc. Inst. C.E.*, vol. lxxvii.

[2] Compiled from tables given by Mr. Andrews (*Min. Proc. Inst. C.E.*, vol. lxxxii. p. 297).

One point of great value, which Mr. Andrews has established, and which is deserving of careful attention, is the desirability of reducing, as far as possible, the internal causes of disintegration in iron or steel structures in sea-water, by avoiding the use of dissimilar metals, and endeavouring to have all plates, bars, clips, rivets, bolts, etc., as nearly as practicable, not only of similar material, but also of the same temper and composition as regards the percentages of combined carbon, manganese, etc., which they contain.

In the year 1871, the iron screw steamship *Gambia* was stranded in Algoa Bay, and became a total wreck. She was built in the year 1860 by Messrs. Leslie & Co., of Newcastle-on-Tyne, and was therefore a comparatively new ship.

In the year 1881, or ten years after the wreck occurred, I carefully measured several of the plates, angles, etc., which lay between high and low water mark, and, for purposes of comparison, I obtained from the builders the original thickness of these.

The following list shows the results of these measurements, and the loss resulting from the ten years of exposure :—

	Original thickness.	Thickness after ten years' exposure.	Loss.
Side skin plates	$\frac{11}{16}$ inch	$\frac{5}{8}$ inch	$\frac{1}{16}$ inch
Angle irons in side ribs	$\frac{9}{16}$,,	$\frac{1}{2}$,,	$\frac{1}{16}$,,
,, reverse	$\frac{1}{2}$,,	$\frac{1}{2}$,,	nil
Longitudinal ties on poop deck ...	$\frac{5}{8}$,,	$\frac{15}{32}$,,	$\frac{5}{32}$ inch
Angles of poop-deck beams ...	$\frac{3}{8}$,,	$\frac{5}{16}$,,	$\frac{1}{16}$,,
Main-deck diagonal ties	$\frac{11}{16}$,,	$\frac{19}{32}$,,	$\frac{3}{32}$,,

On detaching masses of sea-growth from the skin plates near low-water mark, I found red paint still adhering to the plates in some places.

In the letter giving the original thicknesses of plates, etc., which Messrs. Leslie & Co. were kind enough to furnish, they said—

> "We may mention that we have now in dock here for repairs, two vessels built by us about the same time as the *Gambia*, and we find that where the iron has been protected with cement and paint there has not been the slightest deterioration, and the plates of the bottom are now of the full original thickness."

We are thus, I think, justified in assuming that the plates, angles, etc., of the *Gambia* were of their full original thickness when the wreck occurred.

In the measurements above given, it should be remembered that the corrosive action was going on simultaneously on both sides of the iron. This would not usually occur in practice, because hollow piles would be—or, at all events, ought to be—protected from corrosion inside by filling them with cement and sand, or other suitable material. Under-water bracings would probably suffer most, and should therefore be made of extra strength.

In the wreck of the *Gambia* the rate of decomposition appears to have been about one inch in thickness in 320 years, assuming one surface only to have been exposed. This is about seven times as great as that indicated by Mr. Andrews' experiments.

A good many of the *Gambia's* plates were removed and used in the construction of plant. Their strength did not seem to have been impaired in the least degree by the exposure to which they had been subjected.

I mention this because it is well known that the strength of cast iron is greatly reduced by long exposure to the action of sea-water. In fact, the iron is chemically changed, and becomes a kind of plumbago.

Mr. Thomas Stevenson, in his work on "Harbours" (p. 47), says:—

> "In castings at the Bell Rock lighthouse the loss by corrosion has been at the rate of an inch in a century. One of the bars, which was free from air-holes, had its specific gravity reduced to 5·63, and its transverse strength from 7409 lbs. to 4797 lbs., and yet presented no external appearance of decay. Another apparently sound specimen was reduced in strength from 4068 lbs. to 2352 lbs., having lost nearly half its strength in fifty years."

Wrought-iron double-headed rails, weighing about 84 lbs. per yard, were used as bracings in the old breakwater at Port Elizabeth (Cape Colony). These were placed within the tidal range, and were quite unprotected by paint or otherwise. I had no opportunity of ascertaining their actual original section, but after a lapse of about twenty-three years they seemed to have lost very little by corrosion, notwithstanding that they were thickly coated with rust.

The metal, as in the case of the *Gambia's* plates, was perfectly sound and tough when worked up.

The wrought-iron piles of a pier built by the late Sir John Coode at Ramsey (Isle of Man), showed no sign of corroding after a lapse of from eight to ten years. The original coating of paint or black varnish was at that period in good condition, and keeping the piles from rusting below low water, while above low water it was easily maintained.

The same remarks apply to a somewhat similar pier[1] which I constructed at Port Elizabeth, under Sir John Coode's direction, a year or two prior to the Ramsey pier being built.

After a lapse of about six years, some of the piles were examined under water, and on the removal of the sea-growth, which adhered to them in large masses, the paint was found to be undisturbed, and the piles free from rust.

The iron work of a beacon which was removed from the Wolf Rock, after an exposure of thirty years to the corrosive action of sea-water, was found to be in a good state of preservation. It had been protected by a coating of red-lead paint, which was renewed annually.

Some of the internal cement rubble-filling was removed for the purpose of affording space for the stowage of the workmen's tools during the erection of the lighthouse, when the threads of the screw-stays that were embedded in the cement were found to be as perfect as when first made.[2]

In the discussion which followed the reading of Mr. Hooper's paper on the New Ferry and New Brighton piers, at a meeting of the Institution of Civil Engineers, Mr. Beardmore remarked that there was nothing to be feared with regard to the question of the decay of the iron in works of this kind under ordinary circumstances, when reasonable care was taken. There had, however, recently come under his notice the case of a sea-lock which had existed for thirty-five years at the head of a ship canal containing very soft water. When pumped out for repairs, it was found that all the cast and wrought iron portions of the gates, etc., were equally destroyed. Even the spikes of the platform planking had perished, though the timber was perfectly sound. He attributed that intense action of the water upon the iron to the mixture of fresh and salt water, to which the lock was peculiarly subjected, as the soft-water was "locked" down direct into the sea-water. He considered that cast and wrought iron similarly exposed, and for the same length of time, in the Thames would be scarcely affected.

---

[1] This pier was within a hundred yards of the wreck of the *Gambia.*

[2] *Min. Proc. Inst. C.E.*, vol. xxx. p. 6.

Mr. Mallet stated that he had devoted a good deal of attention to the important subject of the durability of iron, and the result of observations induced him to consider wrought iron, upon the whole, a more durable material than cast iron. It was true that some wrought iron corroded faster, but only a little faster, than some cast iron; but the amount of decay and the rate of weakening could be ascertained by measurement in the former, whereas in cast iron the nature of the corrosion was entirely different, and the mass of the material suffered a molecular and chemical change to a considerable and uncertain depth. In sea-water, especially if mixed occasionally with well aërated fresh water, there was the maximum rapidity of corrosion, both of wrought and of cast iron, except that producible by the admixture with sewage-water, which often contained matter that corroded iron almost as fast as diluted vitriol. The protection produced by even a thin film of mud, covering up immersed iron so as to screen it from fresh supplies of water unexhausted of its combined air, had a marvellous effect in preserving it. With regard to artificial modes of preservation by various coatings, in his opinion there was nothing equal to coal-tar, well boiled, with a mixture of finely powdered dry caustic lime.

The iron to be coated should be previously heated to about 600° or 700° Fahr. and be dipped into the mixture. It was useless merely to pay over cold iron with coal-tar, as was often done; the iron must be heated almost to a black-red, and be immersed for some time in the hot tar, which then perfectly dried upon it, and produced a varnish almost as persistent as the japan on a tea-tray. If the iron were previously painted with oil-paint, the coal-tar would not adhere, nor become hard and dry upon it.

Mr. Redman mentioned, with reference to the decay of iron structures exposed to the action of salt or brackish water, that in the estuary of the Thames there were several works which had been completed from twenty to twenty-five years, where the pillars were of cast iron, and which yet remained intact at the present time. The pier at Milton-on-Thames, below Gravesend, designed and carried out by him in 1842–44, was supported on cast-iron columns 3 feet in diameter, the metal being 1½ inch thick, and these were unaffected by such action. The Gravesend town pier, by the late Mr. Tierney Clark, M. Inst. C.E., was on similar supports, the metal being 1¼ inch thick; and these too, though about thirty years old, were similarly unaffected. The cast-iron columns of the Maplin Sand lighthouse, erected about the same time, likewise remained sound, although the metal was only ¾ inch thick.[1]

---

[1] *Min. Proc. Inst. C.E.*, vol. xxviii. pp. 228–230.

CHAPTER VIII.

CONSIDERATIONS AFFECTING THE GENERAL DESIGN OF HARBOURS.

No general rules for designing harbours can be laid down—Preliminary investigation—Survey—Materials available for works—Quarry and work-yard sites—Transport of materials—Description of vessels to be provided for—Beaching-ground—Spending-beaches—Future development of port—Degree of shelter required—Anchorage—Good and bad holding-ground—General requirements of harbours of refuge—Natural features of sites should be utilized.

In designing and constructing sea-works, the ability of an engineer is perhaps best tested by the manner in which he can adapt the materials at his command and the natural features of the site to the particular circumstances of the case. Each different locality has its own peculiarities; therefore each particular case must be considered and dealt with upon its own merits.

It will thus be seen that no general rules can be laid down for the construction of harbours; neither can it be said that one type of breakwater is better than another, or even that one way of constructing breakwaters of the same type can always be adopted with equal advantage.

The only safe course for an engineer to pursue, in designing a sea-work, is for him to carefully investigate the peculiar circumstances of the locality, and, having made himself thoroughly acquainted with them, to adapt the design to the conditions and requirements of the individual case.

The materials readily available for the work, as also the important factor of funds, must always largely influence the decision arrived at.

Preliminary Investigation.—An investigation, such as the one just referred to, should embrace—

(*a*) A comprehensive and detailed survey, the limits of which can be best decided after an inspection has been made of the site and its general surroundings.

Soundings should be taken at sufficiently short intervals to admit of contours being accurately laid down. These should be plotted with special care over rocky ground. The nature of the sea-bed should be ascertained by procuring a sample of the bottom at each sounding, and, when the probable site of the works has been tentatively decided upon, borings may, if necessary, be taken in order to obtain more reliable information than the surface samples afford.

Careful observations should also be made on the tides; currents; height and direction of the heaviest waves; description, extent, and direction of littoral drift; direction and force of prevalent winds; fetch; and so forth.

(*b*) A careful examination of the district, with the view of ascertaining what stone, sand, gravel, and other materials—not forgetting water—are available for the works.

(*c*) A consideration of possible sites for work-yard and quarry, and of the approaches or means of access thereto; also of the means of transporting stone and other materials to the works, and possibly, in some cases, of landing not only materials, but also heavy "plant."

(*d*) A careful consideration of the general facilities which the locality affords for the construction of the work contemplated, including the important question of "labour."

It is scarcely needful to say that, in planning a harbour, the number, size, draught, and description of vessels likely to use it must be kept in view; and also the special kind of trade which may be carried on.

The provision of good beaching-ground and spending-beaches, and of ample quay space, easily accessible by road and rail, are important points to remember, especially in connection with the smaller classes of harbours.

The site to be sheltered should, if possible, provide not only for the immediate wants of the port, but also for increase of trade; and the works should, as far as possible—having due regard to present efficiency—be laid out with a view to their future extension.

The position and direction of the harbour entrance or entrances should receive careful attention (Chap. IX.).

In designing harbours—especially large ones—the *degree* of shelter which it is necessary to afford should be carefully considered, because the cost of a work may be greatly affected by it. Thus a breakwater intended only to break the waves, but not to prevent the broken water passing over into the harbour, need not be carried much above the level of high water, and could obviously be constructed for less money than one with a costly superstructure. On the other hand, for a harbour of refuge, where, in time of war, it might be of importance to ship stores or material, and embark troops with rapidity, a breakwater with a vertical face, adequate depth of water alongside, and a good sheltered quay, would possess great advantages as compared with any of the forms of mound breakwaters, always supposing that suitable inshore quay accommodation and other facilities did not exist.

When the area to be sheltered is such that vessels may be expected to anchor, instead of being moored alongside of quays or tightly packed together, as is too often the case in small fishery harbours, the character of the bottom must be considered with reference to its suitability, or otherwise, as holding-ground.

Good holding-ground is that which is composed of tenacious material—such as tough clay or stiff silty sand—sufficiently soft to admit of anchors taking a good hold.

Bad holding-ground is that where, as in the case of a rock bottom, an anchor either cannot take hold at all, or, having done so, probably takes such a good one that it cannot be got up again. Loose material, such as clean shingle, through which the anchor may draw, is also bad; nevertheless, shingle mixed with loamy sand[1] or other binding substance is often very good.

Where holding-ground is bad, it will be necessary to lay down moorings, secured by screws or in some other suitable manner, according to the nature of the ground.

Under Section ii. of the Report of the Sub-committee appointed to investigate the question of the most suitable site for a harbour of refuge on the east coast of Scotland (1884), the following valuable and practical views are expressed in regard to the leading requirements to be kept in view when choosing a site for a harbour of refuge.

"The term 'harbour of refuge' can be applied either in a *general* or in a *special* sense.

"A harbour of refuge, as understood in a *general* sense, should be in a position in which vessels may obtain shelter under any conditions of wind and weather on a part of the coast that is much frequented, and is without any adequate place of safety into which vessels may run if overtaken by storms. It should possess (*a*) easiness of approach, with convenient ingress and egress; (*b*) good holding-ground and secure anchorage in various depths for all commercial purposes, including the fishing industries, and for a small squadron of war-ships; (*c*) facilities for obtaining ordinary supplies and for executing the smaller class of repairs; (*d*) natural capabilities for the construction of efficient works of defence at a moderate cost.

---

[1] There is a great difference in sands, some being so mobile as to afford scarcely any hold at all, whereas others of a more silty nature are exceedingly tenacious.

"A 'special' or 'national' harbour of refuge is one whose position is influenced mainly by strategical considerations and imperial policy, a refuge harbour in the sense of shelter from an enemy as well as from storms. In a 'national' harbour fresh considerations present themselves, such as the following:—

"(*a*) Its position should be central in reference to the defence of some important part of the coast and of the shipping frequenting it, and at the same time convenient for observation of the movements of an enemy.

"(*b*) A larger area of anchoring-ground in depths sufficient for the heaviest-draught ships of war is required than in the 'general' harbour of refuge.

"(*c*) It should be, with a view to the concentration of troops and military stores, in connection with the railway system of the country, and should possess facilities for the supply of coal, and for the smaller and immediate repairs demanded by a squadron of large ships.

"'Local' harbours of refuge are those of which the sites can be determined only by local demands, and their area and capabilities by local requirements, it being understood that the term 'harbour of refuge,' when applied even under these limited conditions, carries with it easiness of approach, and a sheltered anchorage at all states of tide for vessels of a moderate draught of water."

In laying out a plan for sea-works, advantage should be taken of any natural features which can be turned to account, such as channels or indentations of the coast, ridges of rocks, and so forth. The adaptation of designs to such features must, however, be kept within reasonable limits; otherwise, so far from being advantageous, they may prove detrimental to the work.

CHAPTER IX.

ESTUARY HARBOURS—GROUND PLANS OF HARBOURS—ENTRANCES.

Estuary harbours—"Bars"—Lagoons—Removal of "bars"—Concentration of ebb current—Importance of large tidal compartment—Protection of ebb current—Site of entrance—Maintenance of depth—Relative value of upland and tidal waters—Borings on site of proposed entrance, etc.—Physical and nautical requirements often opposed to each other at harbour entrances—Ground plans of harbours—Wave expansion—Direction of main entrance—Parallel jetties—Isolated breakwaters—Harbours with two entrances—Roadsteads—Advantages of deep water at entrance—Strong current across harbour entrance objectionable—Widths of entrances—Reduction of waves—Relative advantages of embayed and salient sites for harbours.

WORKS undertaken with the view of improving estuaries, or the entrances to rivers, constitute one of the most important, and at the same time difficult, sections of harbour engineering. To deal with the subject in an exhaustive manner would involve a fuller inquiry into river engineering than it would be convenient to introduce into this volume; nevertheless, its importance is such as to call for somewhat more than a passing notice.

A river-mouth in its natural state will, with but few exceptions, be found "barred" by banks of silt, sand, or shingle. This condition of things is brought about by natural causes, which may be briefly stated as follows:—

The material carried in suspension or caused to travel along the bed of a channel by the river waters, upland or tidal, requires a certain velocity of current to enable it to remain in suspension or be rolled along the bottom.

When the outgoing current encounters the ocean, or other large body of water, its velocity is checked, and at the point where it becomes so much enfeebled that it can no longer hold the material in suspension or maintain its motion along the bottom, the matter settles down and accumulates, thus forming a bank or "bar."

Waves play an important part in the formation of bars, not only by checking the outgoing current, but by throwing up material, and endeavouring to establish and maintain the line of beach past the river-entrance in spite of the ingoing and outgoing currents.

When waves impinge on a beach at an acute angle, they cause the material of which it is composed to travel along the coast, and their tendency is to drive it into river channels and estuaries; whereas the action of the ebb current is to drive it out and keep the channel clear.

A battle between these contending forces is, therefore, continually being waged; but the wave power is, as a rule, more than the river current can cope with, the result being that the river-channel is deflected, and a ridge, forming its submerged seaward bank, is heaped up by the waves—aided, possibly, by littoral currents—and by them pushed more and more landward till at length it runs parallel, or nearly so, to the coast-line.

In extreme cases, especially in countries where winds blow steadily in one direction for long periods, and where long droughts occur, river-mouths are often completely closed, the water thus impounded spreading out and forming lagoons of greater or less extent, until, on the occurrence of a freshet, the river bursts through its barrier, usually at a point nearly in the direct normal line of the channel.

The following woodcut, indicating the deflection of a river channel from *a* to *c*, may be of service in illustrating the manner in which the contending forces act:—

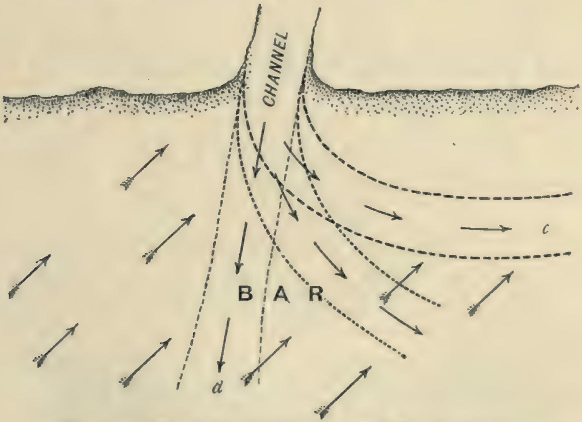


FIG. 21.—Feathered arrows indicate assumed direction of waves.

No sooner has the river broken through this barrier and formed a new channel, than the waves again begin to baffle and deflect it, and the whole process is repeated over and over again, the direction of the channel being the resultant of the forces at work.

Where a river-mouth is wide and exposed to gales from various quarters, the routine above described is less regular, and a bar, intersected by various channels, is usually formed.

In designing an estuary harbour, the aim of the engineer must be to direct and aid the natural forces tending to remove the bar and keep the channel open, and to protect them from those having a counter effect.

This will be best accomplished by (*a*) so concentrating and directing the currents, more especially on the ebb, that their whole scouring power shall be utilized in forming and maintaining a channel so far seaward that the matter carried down by the outgoing tide shall be held in suspension until it is brought under the influence of cross littoral currents, or into such deep water as will ensure its dispersion before it can be carried back into the harbour again.

(*b*) To increase, as far as possible, the volume of water passing over the bar at each tide by enlarging the tidal compartment within the estuary or harbour by means of dredging, and by the removal of such sharp bends or other obstructions in the channel as might retard the tidal flow and prevent the tidal compartment, especially in its upper reaches, receiving its full complement of water.

It has been proved to demonstration over and over again that reclamations or other works reducing the capacity of the tidal compartment, and consequently the quantity of tidal water passing through a harbour-entrance, injuriously affect the depth of water at the entrance, in proportion to the amount of water thus excluded, the converse being equally true.

(*c*) To protect, by means of breakwaters, the outgoing current from the deflecting effect of prevalent heavy seas for such a distance as will enable it to carry the matter in suspension well out to sea.

These are the broad principles upon which estuary harbours must be treated, but only careful study of local conditions and experience in dealing with such matters can ensure success in any individual case.

The position of an entrance is to a great extent governed by the depth of water which it is sought to obtain; but the *exact* point at which to terminate protecting piers or training banks is frequently, in the early stages of a work, a matter of doubt even with the most experienced engineers. It is therefore important that works of this description should be laid out upon such lines as to admit of their easy extension, should such appear to be desirable, as the works proceed.

Excepting under the most favourable conditions, and where the volume of upland water is great, a certain proportion of the material brought in by the flood tide will at slack water be deposited in the river-channel in excess of what is removed by the ebb. In such cases dredging must be resorted to in order to keep the channel clear; and it may here be stated that there are comparatively few instances where natural forces can be made to maintain a channel without such assistance. This represents expenditure for maintenance, and is therefore distasteful to those who have to provide the necessary funds. It is, however, better to admit the fact at the outset than to spoil an entrance by unduly contracting it and attempting impossibilities.

The relative value of upland and tidal waters necessarily depends in a great measure upon the proportion which they bear to each other. This is, however, not always the case to so great an extent as might at first appear. Owing to the greater density of salt water, the outgoing fresh water floats upon it, and the scouring power of the latter is thus rendered inoperative during the whole period of flood tide, inasmuch as the salt water runs in as an undercurrent, whilst the fresh water flows out over it.

This is often very noticeable while bathing near a river-mouth, not only the difference in the direction, but also in the temperature of the upper and under currents, being clearly discernible.

Admiral Sir Edward Belcher states—

> "The ships of war fitting at Woolwich were supplied with fresh water from the Thames, pumped up from alongside at the turn of the tide, and up to the first quarter of flood; but the end of the pump or

hose was never allowed to be more than 2 feet below the surface of the river. If that precaution was neglected, and the hose was inserted 3 feet below the surface, salt water was immediately pumped up."[1]

The late Mr. David Stevenson, referring to observations on the River Dee at Aberdeen, says—

> "It was then clearly ascertained that on certain occasions there was a perceptible outward current *at the surface* during the whole period of the flood tide, and that simultaneously there was a current of sea water running inwards. The salt water flowed in underneath, raising up the fresh water, the fresh water in reality running out over the top of the salt water."[2]

This tends to show that the tidal water should be chiefly relied upon for the maintenance of channels at river-mouths, and that every effort should be made to increase the volume and efficiency of the tidal flow.

The value of upland water must not, however, be underrated, because during the ebb tide it combines with the tidal water and increases the scouring effect.

Before deciding upon the site of an entrance or navigable channel, the nature of the bottom ought to be ascertained by a series of borings or probings. These should be carried to the full depth of channel contemplated;[3] and in the event of rock being found at such a level as to interfere with the forming or deepening of the channel on the site first selected, other borings should be taken with the view of finding a more desirable one.

Such an investigation, although it may prove somewhat costly, can scarcely fail to be of great value in revealing the facts of the case, and enabling recommendations to be made with greater confidence.

Rock may be removed by dredging, after it has been broken up either by blasting or by some of the other methods now adopted. They are, however, all costly; and should such work have to be performed in a breaking sea upon a bar, its difficulty and cost would be greatly increased.

---

[1] *Min. Proc. Inst. C.E.*, vol. xxi.

[2] Ibid., vol. xxi.

[3] In considering the depth requisite for vessels of any given draught, due allowance should be made for waves, and also for *send*, or the plunging of vessels in a rough sea, which may amount to several feet below their normal line of flotation. For vessels of moderate size, two-thirds of the height of the waves, trough to crest, is sometimes taken as the greatest *send*, one-half the height of the waves being allowed for vessels of larger size.

Stiff clay and similar material may be readily removed by ordinary dredging, with permanently good results; but dredging on a bar composed of sand, gravel, or mud, will, as a rule, prove fruitless, unless aided by training and protective works, inasmuch as the natural forces at work will generally replace the material almost as fast as it can be removed.

It is often difficult, if not impossible, to so design a harbour-entrance that it shall meet all exigencies, seeing that the physical and nautical requirements are usually opposed to each other. The relative importance of the several requirements must therefore be duly considered, and the entrance be designed accordingly.

As an illustration, assume that, with the object of obtaining very smooth water within a harbour, avoiding a "run" up a river-channel, and increasing the scour upon a bar, an entrance should be made unduly narrow, and its direction be such as to cause heavy seas to run across it instead of into it. A vessel entering such a harbour during a gale would be exposed to a "beam sea;" and, should the tide be ebbing at the time, she would also probably meet a strong outward current, which, coupled with the narrowness of the entrance, might easily involve her in destruction.

On the other hand, when an entrance is so arranged as to afford easy ingress to vessels during heavy gales—as that of a harbour claiming to be a refuge harbour undoubtedly should be—it almost of necessity admits heavy seas, not only by reason of its direction, but also of its width.

Waves, after passing the pier-heads, may, however, be quickly reduced by so designing the ground plan of a harbour as to afford ample area, and especially width, for their expansion (Fig. 22, p. 156), and by a judicious arrangement of spending-beaches.

When very still water is required, an inner harbour with a well-sheltered entrance is often constructed.

There can be little doubt that the main entrance to a harbour should face in such a direction as to admit of vessels taking it *with ease* during the worst gales.

Much will naturally depend upon its width and form, but it should be so planned as to freely admit vessels when running on a course coincident with the direction of the heaviest seas, or not deviating from it to a greater extent than from two to three points.

The form of entrance represented by Fig. 23 is objectionable, inasmuch as waves are likely to be led up the channel by

⇛—— *Direction of heaviest seas.*
→ ,, *drift.*
⇝—— *Outgoing current from harbour.*

Fig. 22.

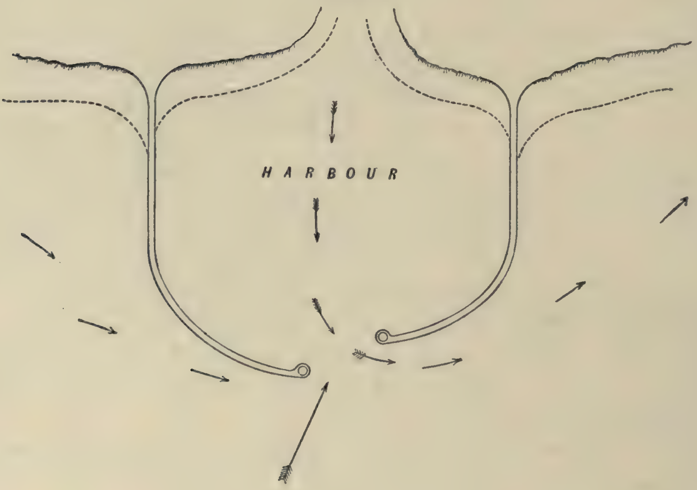


Fig. 23.

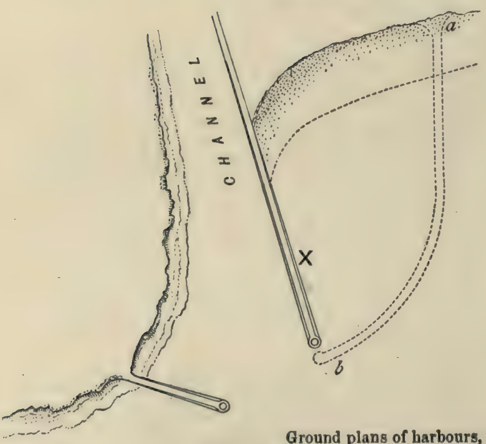
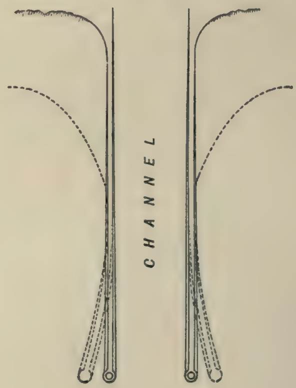


Fig. 24.



Ground plans of harbours, etc.

the pier X, the area enclosed being insufficient for their proper reduction.

A preferable design would be that indicated by the dotted lines, pier *a*, *b*, or the dead water embraced by it, being quite as serviceable as pier X in training the channel, and at the same time affording a much greater area for the expansion of waves and for the shelter of vessels immediately on their entering the harbour.

FIG. 25.

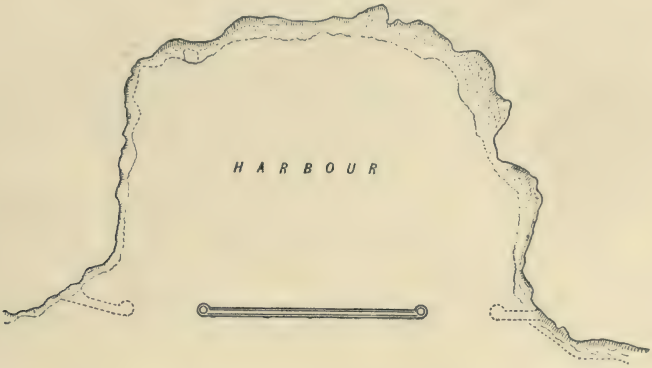
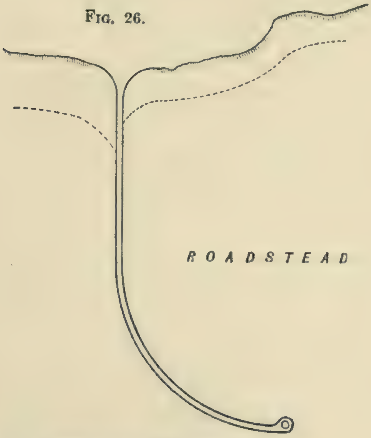


FIG. 26.



Ground plans of harbours, etc.

Entrances formed by jetties projected from a shore, and running either parallel to each other, or diverging in trumpet-like form (Fig. 24), are undesirable in many ways. They afford no facilities for the reduction of waves—indeed, a trumpet-shaped entrance has the reverse effect—and they are liable to lead heavy seas up the channel, thus frequently causing an inconvenient range at wharves or shipping-berths, even when these are situated far from the harbour-mouth. Moreover, vessels entering the port on the ebb tide, or leaving it on the flood, have the force of the current concentrated upon them, and they cannot get out of each other's way with the same facility as when more width is given.

Instances are not wanting where, owing to the roughness of the sea within a narrow entrance-channel, the leading vessels of those seeking shelter during a gale have collided and completely blocked the channel, the following ships running in on the top of them.

The fact that piers projected in this manner do not enclose an area such as to appreciably enlarge the tidal compartment, and so increase the scour at the entrance, is a conspicuous defect, the more so since the construction of such jetties almost invariably causes an advance of the foreshore, and a consequent reduction of depth.

The employment of dredgers in such channels is often attended with much inconvenience to the shipping.[1]

Isolated breakwaters, as at Plymouth, Cherbourg, and other places, naturally provide an entrance at either end, between the breakwater and the shore (Fig. 25, p. 157). This gives mariners a choice either in entering or leaving the harbour, and sometimes proves very convenient.

Additional stillness within a harbour, coupled with the advantages of a double entrance, may be obtained by protecting the main entrance by means of an outlying breakwater placed at a suitable distance to seaward of it. This system has been adopted at several of the Mediterranean ports, and at other places.

Single breakwaters projected from the shore, as at Holyhead, Portland, Dover (Admiralty pier), etc. (Fig. 26, p. 157), can scarcely be said to form harbours, the areas so sheltered partaking more of the nature of roadsteads. The amount of shelter afforded in such cases depends much upon the direction of prevalent gales and the trend of the coast; and it may, as at Holyhead and Portland, very nearly approximate to that of close harbours.

---

[1] The foregoing remarks must not be taken as applying to the *gradual* enlargement of a river-channel towards its mouth.

It will sometimes be found beneficial to extend the end of the weather pier—by which I mean the one on the side of the channel or harbour from which the heaviest seas come—slightly beyond that of the lee pier; the object of such overlap being to partially shut out heavy seas from the harbour, to afford some shelter to vessels before coming abreast of the lee pier in entering, and to give them a better " loose " in leaving the port.

The passage of drift—if it should, as is usually the case, proceed from the direction of the heaviest prevailing seas—is also aided in this way; and the outgoing current, with its detritus in suspension, is enabled to trend away to leeward, clear of the entrance, while yet deriving some shelter from the weather pier.

The extent, if any, to which this overlapping ought to be carried can generally be best decided as the works advance, and it is seen how the entrance works (Fig. 22, p. 156). If the overlapping be carried too far, it is apt to create an eddy, and cause a deposit of drift under lee of the weather pier. It is also objectionable in causing vessels, when entering, to encounter more or less of a beam sea.

Care should be taken not to give a pier such a direction as to admit of its leading waves up to an entrance. Advantage should be taken of any physical conditions tending to mitigate the force and dangerous character of waves at an entrance. Thus, with the view of preventing their breaking, as well as of affording other facilities, an entrance should be placed in the deepest water possible, it being borne in mind that every additional foot of water at an entrance greatly enhances the value of a harbour.

A *strong* current across an entrance should, when possible, be avoided, it being remembered, as stated in a former chapter, that the projection of close piers across a coast current will inevitably increase its strength past the pier-heads.

The width of an entrance should be regulated (*a*) by the class of shipping frequenting a port; (*b*) by the area of the harbour and the capacity of the tidal compartment; (*c*) by the quantity of upland water to be discharged; (*d*) by the strength of the current running past it; and (*e*) by the extent, keeping these considerations in view, to which it is possible to shut out heavy seas.

The narrower the entrance, within reasonable limits, the more will the action of the ebb and flood currents be concentrated, and the more effective will they be in maintaining an open channel. A narrow entrance also, by admitting less sea than a wider one, produces quieter water within the harbour.

Care must, however, be taken not to so contract an entrance as to injuriously check the flow of the ingoing current, otherwise the volume of water entering the tidal compartment may be so reduced as to react upon the bar.

It would also be bad engineering to so increase the velocity of the current at a harbour-mouth as to interfere with navigation. Much inconvenience has been experienced, and many shipwrecks have been caused, by the outgoing current from a harbour so checking the way of approaching vessels—I refer especially to sailing-vessels and fishing-boats—just as they have been on the point of entering, that they have broached to, missed the entrance altogether, and been driven ashore. Furthermore, a strong current running counter to storm waves sets up a dangerous sea, in which vessels are likely to become unmanageable.

Experience shows that the velocity of the outgoing current from a harbour should not exceed 3½ to 4 miles per hour.[1]

The widths of entrances of existing harbours vary to so great an extent—say from under 100 feet to over 3000 feet—that, without stating all the physical and other conditions which, in each particular case, had to be taken into consideration in determining such widths, a list of them would be of little use, and might even mislead.

For some close harbours of magnitude, where the problem is simplified by the absence of upland water and abnormal conditions, entrances varying in width from about 500 feet to 850 feet have been adopted or proposed. Thus, at Madras an entrance of 550 feet in width is proposed for a harbour having an area of 220 acres; at Peterhead harbour of refuge an entrance of 600 feet is proposed, the area being 340 acres; at Kingstown the width of entrance is 750 feet, the area of the harbour being about 250 acres; and at Ymuiden the entrance is 850[2] feet wide, the area being also 250 acres.

Miles
per hour.
[1] A current with a velocity of 0·4 will move fine sand.
„ „ 0·5 „ coarse sand.
„ „ 0·6 „ fine gravel.
„ „ 0·7 „ gravel the size of beans.
„ „ 1·6 „ shingle 1 inch diameter.
„ „ 2 to 2·5 „ shingle 2 to 3 inches diameter.

[2] This entrance has a strong current—about 4 knots per hour—running past it.

In fishery harbours, with areas varying from, say, 6 to 10 or 15 acres, entrances of from 100 to 200 feet in width are commonly adopted. Thus Lowestoft outer harbour, with an area of about 15 acres, has an entrance of 150 feet in width;[1] while the north and south old harbours at Peterhead, each with an area of about 6 acres, have entrances of 100 feet in width.

Reduction of Waves.—In the case of a harbour which opens out quickly within the pier-heads, waves running straight in do not disturb the tranquillity of the water to such an extent as might be supposed, because immediately they pass the entrance they rapidly expand, and their height is thereby at once reduced.

The late Mr. Thomas Stevenson, C.E., has given us a formula for calculating the reductive power of harbours, by which is meant their power to reduce the height of waves after passing within the entrance.[2]

It is based upon the expansion of the wave, which is inversely proportional to the square roots of the breadth of entrance and the greater breadth within the piers upon any line measured at a given radius from the entrance.

The formula is as follows:—

$$x = \mathrm{H}\frac{\sqrt{b}}{\sqrt{\mathrm{B}}} - \frac{\left(\mathrm{H} + \mathrm{H}\frac{\sqrt{b}}{\sqrt{\mathrm{B}}}\right)\sqrt[4]{\mathrm{D}}}{50}$$

Where H = height of wave at entrance, in feet.
b = breadth of entrance, in feet.
B = breadth of harbour at place of observation, in feet.
D = distance from mouth of harbour to place of observation, in feet.
x = reduced height of wave at place of observation, in feet.

When H is assumed as unity, the formula assumes its simplest form—

$$x = \frac{\sqrt{b}}{\sqrt{\mathrm{B}}} - \frac{\left(1 + \frac{\sqrt{b}}{\sqrt{\mathrm{B}}}\right)\sqrt[4]{\mathrm{D}}}{50}$$

and x will come out a fraction, which will represent what may be called the *reductive power* of the harbour at the point for which the calculation has been made; and by multiplying the height of any wave at the entrance by the fraction x, its reduced height is found at once.

---

[1] The inner harbour, 10 acres in area, has an entrance 100 feet wide.

[2] "Report of Royal Commission on Harbours of Refuge, 1859," vol. i. p. 240.

In order to show the correspondence between the results of calculation by the formula and the actual observations, Mr. Stevenson gives the following table, which contains averages of the observations at the places named.

The number of observations made was very great, those for Buckie alone being upwards of 2000.

Name of harbour.	Calculated reductive power.	Observed reductive power.
Buckie, 1st point of observation	·649	·534
,, ,, ,, ,, ...	—	*·570
,, 2nd ,, ,, ...	·464	·323
,, ,, ,, ,, ...	—	*·394
,, 3rd ,, ,, ...	·233	·207
,, ,, ,, ,, ...	—	*·342
,, 4th ,, ,, ...	·186	·157
,, ,, ,, ,, ...	—	*·289
,, 5th ,, ,, ...	·143	·136
,, ,, ,, ,, ...	—	*·158
,, 6th ,, ,, ...	·119	·139
,, ,, ,, ,, ...	—	*·175
,, 7th ,, ,, ...	·209	·222
,, ,, ,, ,, ...	—	*·289
,, 8th ,, ,, ...	·274	·232
,, ,, ,, ,, ...	—	*·368
,, 9th ,, ,, ...	·427	·339
,, ,, ,, ,, ...	—	*·491
Fisherrow, 1st, on west side	·478	·472
,, 2nd, on east side	·430	·384
Macduff, 1st, 165 feet from inner entrance	·440	·600
,, 2nd, 340 feet from inner entrance	·420	·532
Sunderland, 1st, at stairs on south pier ...	·440	·385
,, 2nd, at entrance to south dock	·1015	·1023
Kingstown	·307	·374

The results marked thus * were derived from a series of observations made during the great gale of November, 1857.

In these days of steam, when tugs are available at most ports, the form and general arrangement of entrances, from a nautical point of view, is not of such vital importance as it used to be before such facilities existed; nevertheless, in a gale of wind hawsers cannot always be trusted, and there can be no doubt that entrances should, where possible, be so designed that vessels under sail could either take a harbour or leave it without such help.

In the case of harbours frequented by fishing fleets, the subject is one of paramount importance.

Considerable difference of opinion exists as to whether the entrance to a harbour, or indeed the harbour itself, should be upon a receding or a salient part of the coast.

It is contended, on the one hand, that the entrance should be placed well back—in fact, in the most deeply embayed or leeward portion of a coast—so that any vessel, finding itself embayed, would be able to make for the harbour, and probably by so doing avoid being wrecked.

This argument no doubt holds good for the particular bay or receding portion of the coast where such a harbour may happen to be; and there are many sites the importance of which, commercially considered, would fully warrant this view of the case being taken. But from a refuge point of view, in order to adequately provide for the wants of embayed vessels along a coast, it would obviously be necessary to provide a harbour of refuge in every bay.

On the other hand, it is argued that in bad weather vessels ought to keep well off a lee shore until driven to seek shelter; and the construction of harbours at salient points of the coast is advocated on the ground that they could be more easily "made," especially in misty weather or during snowstorms, by vessels in the offing, or by those approaching the coast from over the sea, and that they would be most useful to general passing trade.

It is further argued that vessels using the harbour for purposes of shelter would be able to get away to sea sooner, as the gale moderated, than they could do from an embayed harbour: and also that, in the event of a vessel in a gale of wind failing to make the entrance of a salient harbour, she would have a chance of beating out again; whereas, if she failed to fetch the entrance of an embayed harbour, she must inevitably go ashore or be wrecked on the breakwater.

Therefore, when once a vessel runs for an embayed harbour, she is bound to go in or be wrecked; and she must take her chance of the entrance being blocked or crowded with other ships, and also, in the case of a tidal harbour, of there being water enough to admit her when she arrives.

The salient position of Holyhead harbour, on the west coast of England, and of the natural roadstead of the Downs on the east coast, is found to be of great advantage for the reasons above named.

This question, like so many others, is, however, one in regard to which no general rule can be laid down. Much will depend upon the size and shape of the bay under consideration, and the general trend of the coast. The existence, or otherwise, of strong littoral currents, the direction of prevalent gales, the depth of water, and many such-like considerations, will all affect the question; and it may be safely assumed that they will not be the same in any two cases. Excepting, perhaps, in large undertakings of a national character, facilities for local trade will largely influence the question.

The subject of silting is also one which must not be overlooked, a harbour placed in the bight of a bay being much more liable to silt up than one occupying a more prominent position, where its threshold would be swept by the shore currents.

CHAPTER X.

FISHERY HARBOURS.

Difficulty of designing small harbours—Injury inflicted upon boats by "range"—Inner basins and spending beaches—"Booms"—Entrances—Risks incurred in entering tidal or barred harbours—Fish deteriorate by delayed delivery—Berthage—Quay space—Water area—Loss incurred for want of proper harbour accommodation—Dimensions and equipment of herring fishing-boats.

THE importance of the fishing industry is such that I think it well to devote a short chapter to what may be termed "fishery harbours."

The amount of money available for constructing harbours of this class is often very small, and the limited area which it is thus possible to shelter constitutes one of the greatest difficulties in designing them.

It is frequently not possible to arrange their entrances in such a manner as to shut out heavy waves, and at the same time admit of boats entering with safety; hence, for want of sufficient area over which the undulations may expend themselves, the range within these small harbours, during rough weather, is often excessive, and much injury is at times inflicted upon the fishing-boats which frequent them.

I have before me now the report of a meeting which was held not very long ago, respecting one of the northern Scottish fishery harbours of no small importance. It states—

> "From Saturday night to Monday morning the fishermen were in continual watch upon their boats, which were cooped up in the *inner basin*, and were dashed against each other by a heavy swell and current caused by a strong westerly gale.
>
> "The recent experience has been a terrible one, and if the damage done to the hundred boats were reckoned at the modest sum of £10 each, the worth of property lost to the fishermen in that short time would be £1000."

As an indication of the manner in which these small harbours are affected by range, I refer the reader to the plan of Peterhead harbours, given in Fig. 27.

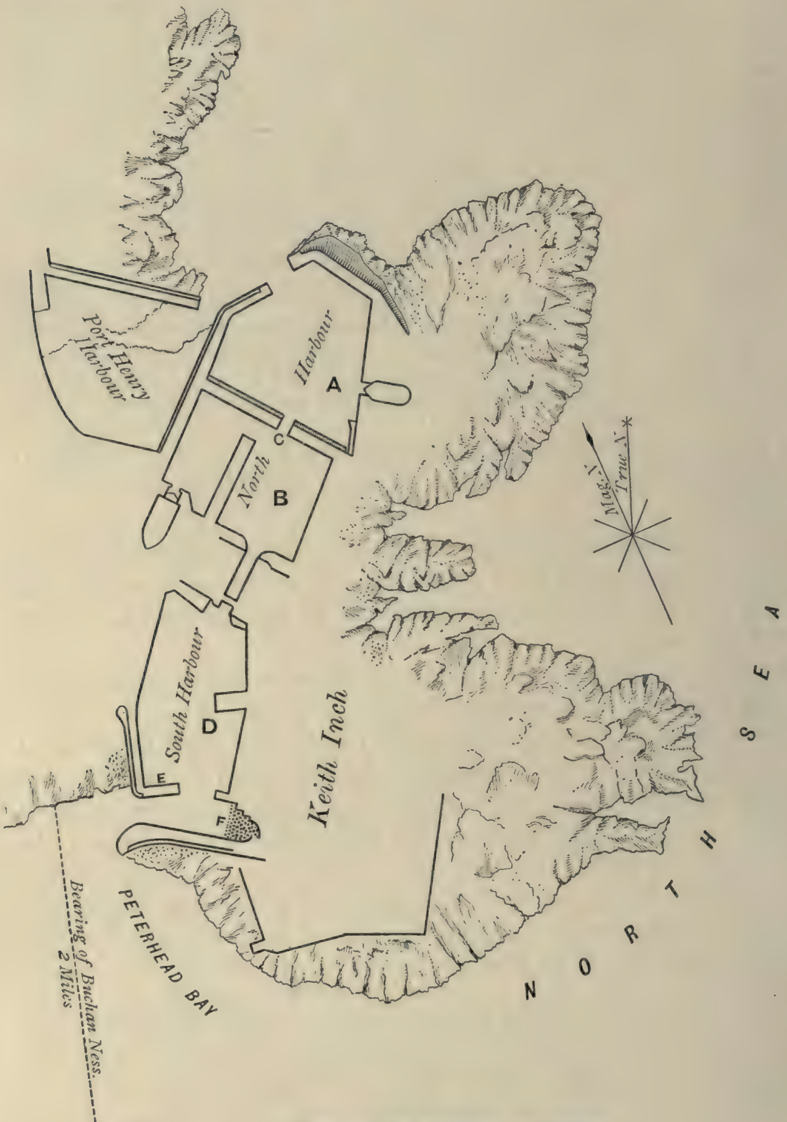


FIG. 27.—Plan of Peterhead (old) harbour.

These harbours are amongst the best of their class; nevertheless, with the wind anywhere from north round to east, with only a moderate sea, no boats can with safety lie in the outer north harbour, A; and during rough weather there is considerable range in the inner harbour, marked B, unless booms are placed across the entrance C, as is usually the case.

Inconvenience is similarly felt in the south harbour, D, during rough weather, with the wind anywhere from east-south-east round to south-south-west, the range often being very troublesome, notwithstanding that the entrance is turned away from the waves, and the swell is cut off to a great extent by the cross-wall E, and neutralized by the spending beach F.

Although the construction of inner basins and spending beaches may, in some cases, but imperfectly accomplish the object aimed at, as will have been gathered from what has just been said, there is probably no more efficient mode of reducing the range in these small harbours than by having recourse to them.

The system of turning away the main entrance from the waves, to such an extent as to sacrifice safety of access, should without doubt be avoided; and spending beaches and room for wave-expansion should be provided to the fullest possible extent. Apart from their primary object of reducing range, spending beaches, with easy slopes of, say, 1 in 8 or 1 in 10, are very useful for hauling up boats upon during the winter months, or during bad weather, or at other times for purposes of cleaning or repair.

Swell may be completely excluded from the inner basin of a harbour by closing its entrance with booms, in the manner already referred to. These are usually formed of logs of timber extending across the entrance, and fitting into grooves provided for the purpose at either side of it. The logs are placed one upon the other, and they must be made to extend to the bottom, otherwise the swell will pass under them.

The requisites for a good fishing harbour are necessarily in many respects identical with those of other harbours, as set forth in Chapter VIII. The value of berthage and quay space seems, however, to point to the adoption of one or other of the vertical types of piers, whenever practicable, in constructing harbours of this class.

The importance of having an entrance or entrances through which boats can enter and leave without difficulty at all times of the tide, and in any wind, can scarcely be overrated.

If a harbour is "barred," or tidal—by which I mean dry, or nearly so, at low water—fishermen frequently incur loss, and run serious risks, by having to remain at sea until the tide has flowed sufficiently to allow of their entering.

The risk of entering a harbour under such circumstances is sometimes much increased by the sea becoming rougher during the time that the tide is making, and not infrequently by a number of boats making a simultaneous rush for the harbour as soon as there is water enough to admit them.

During a storm which burst on the east coast of Scotland during the fishing season (August) of 1848, fifty-one boats and thirty-one lives were lost at the entrance of Peterhead harbour from this cause, the boats getting wedged together so that they could not move, and having to lie exposed to the full fury of the gale in a beam sea. The boats at Wick suffered in a similar manner, but not to quite so great an extent.[1]

When boats cannot gain a harbour in good time, so as to deliver their fish, the value of the fish decreases rapidly. Thus, in many ports, if herring are not delivered before noon, the price falls to the extent of, it may be, five to ten shillings per cran.[2] The reasons for this are: (1) The boats, as a rule, have all their nets hauled in by 6 a.m., and if the fish lie bulked in the boats over a certain time, they heat and become soft. In this state they are unsuitable either for curing or for the fresh-fish trade. (2) The fresh-fish dealers usually make their arrangements to suit the train service, and these are completely upset if the boats are not fairly punctual; in consequence of which, and also on account of the fish having deteriorated in the manner above described, they will often not buy them at all.

In a fishery harbour there should be sufficient space for all the boats that frequent it to lie together without crowding, enough depth of water in every part of it to enable them to be afloat at all times of the tide, slipways for hauling them up when necessary, and proper facilities for taking in their nets and gear, and landing their fish. The quays should not be higher than necessary, and they should be in direct communication with the railway system of the country, so as to facilitate, as far as possible, the transit and distribution of fish, its value being in this way much enhanced.

---

[1] There was a marked diminution in the loss of life and property amongst the fishing-boats at Great Yarmouth when the bar was deepened so as to give a depth of 10 feet of water at low spring tides, the depth previously having been only about 2 feet.

[2] The herring "cran" measure has a capacity of 37½ imperial gallons. A "last" of herrings is equal to about 10 crans. It is, however, not a measure of capacity, but a Dutch count of ten thousand, 132 herrings being by custom given as 100.

A common defect in fishery harbours is the want of sufficient berthage and quay room. Boats are usually berthed with their sterns to the quay; each boat therefore occupies a length of quay equal to its beam, plus, say, 2 feet for fenders; or about 22 feet in all. If possible, from 1½ to 2 acres of quay space per 100 boats should be allowed for curing, packing, and other purposes; and no quay, where practicable, should be less than 40 feet in width. Each acre of water space will accommodate about 40 boats of 50 to 55 feet keel.

The annual loss sustained by fishing fleets, in consequence of the inadequacy of fishery harbours to meet their wants, is ably pointed out in a prize essay, entitled "Harbour Accommodation for Fishing Boats," a copy of which its author, Mr. Archibald Young (Advocate), late inspector of salmon fisheries for Scotland, has kindly sent me, and from which I quote as follows:—

> "The crew of a fishing-boat will hang by their nets to the last moment when they know that they are near a harbour to which they can run *at any time of the tide.* But the case is far otherwise when they know that the neighbouring harbour has a shallow entrance accessible only for an hour or two during each tide.
>
> "In such cases it is impossible that the fishing can be prosecuted to the best advantage. Mr. Boyd, agent for the trustees of Peterhead harbour, stated, in a paper read before the Herring Fishery Commissioners in 1877, that 'during the last ten days of the herring-fishing season of 1876, the yield of the fishery at Peterhead would have been increased by at least £60,000, if adequate and safe harbour accommodation had been available.' And Captain David Gray, the most experienced and successful of the Peterhead whaling captains, and who is also intimately acquainted with Peterhead harbour and the herring fishery in the vicinity, said that 'in *doubtful* weather the boats do not go to sea at all. During the present season some of the boats have not been ten times to sea. Last season there was a great body of herrings off the town, which was ascertained from the fact that the few boats that did go to sea had heavy takes, and it was estimated that the fishermen lost herrings worth over £50,000 from being unable to go to sea.' He further stated, 'This very

morning the harbour was blocked up; the boats were bound to run for the south harbour, and they were coming in one on the top of the other. It is a vital question to the herring trade to increase the harbour accommodation.'

"The fishery officer at Fraserburgh, gave evidence to the same effect, estimating the loss to the Fraserburgh fishermen, arising from insufficient harbour accommodation, at 64,000 crans of herring, valued at £80,000."

Since the foregoing statements were made, the harbours of Peterhead and Fraserburgh have been considerably improved; nevertheless, the depth of water at their entrances is still small, being only from 5 to 6 feet at low water springs, and these improvements have to a certain extent been neutralized by a much larger class of boats being now employed in the fishing than those formerly in use.

At the present time, the average number of nights during the herring fishing upon which the Peterhead boats do not venture out, owing to threatening indications in the weather, is twelve. The average catch per boat per night, for the whole fishing, which lasts for forty days, is about 7½ crans; but during the height of the season the catch *for a single night* often averages fully thirty crans per boat.

Thus, assuming 600 boats to be engaged, the loss of one night's fishing represents, at 7½ crans per boat, 4500 crans, or 54,000 crans for the twelve nights. Assuming these to be worth 20*s.* per cran, which is a fair average price, we have £54,000, and this, capitalized at twenty years' purchase, represents a sum of no less than £1,080,000 for the town of Peterhead alone.

This surely demonstrates the value of *good* harbours, even should the fishing industry alone be considered, and that from a monetary point of view.[1]

The following table contains some information about fishing-boats which may be of interest:—

---

[1] The value of the herring yearly brought into the chief fishing stations on the Aberdeenshire coast is at least equal to the land rental of the county; and the value of the herring cured in 1880 in the whole of Scotland exceeded by half a million sterling the rental of the nine northern counties ("The Further Development of our Sea Fisheries," by R. W. Duff, Esq., M.P. D. Wyllie & Son, Aberdeen).

Table containing Information relative to Boats used in the Herring Fishing (Scotland).

Description of boat	Length of keel.	Beam.	Draught.		Number of nets carried by each boat.	Size of nets.	Crew.*	Approximate value with outfit complete.	
			In ballast.	Laden.					
	feet.	feet.	feet.	feet.		yards.			£
Largest size (decked)	62	21	6½	8½	60 to 70	60 × 18	7 men	Hull, with spars, anchors, and chains complete	410
								Sails and ropes	75
								Nets, say 60, with corks, buoys, and gear complete, at £3 each	180
								Total ...	665
Usual large size (decked)	54	19½	5½	7½	55	ditto	6 men 1 boy	Hull, spars, etc., as above	270
								Sails and ropes	50
								55 nets, etc., at £3 each	165
								Total ...	485
Average size (decked)	50	17½	5	7	50	ditto	6 men 1 boy	Hull, spars, etc., as above	250
								Sails and ropes	45
								50 nets, etc., at £3 each	150
								Total ...	445
Small size (decked)	46	16	4½	6½	40	ditto	6 men	Hull, spars, etc., as above	230
								Sails and ropes	40
								40 nets, etc., at £3 each	120
								Total ...	390

* About 5 persons per boat are employed ashore.

CHAPTER XI.

VARIOUS TYPES OF BREAKWATERS.

Classification of breakwaters—Vertical types—Mound types—Action of waves against vertical faces—Timber-framed breakwaters—Breakwaters with side walls of masonry and hearting of loose rubble—Kilrush pier—Wick breakwater—Danger of loose rubble hearting—Advantages of using large blocks in constructing breakwaters—Breakwaters formed of concrete blocks laid in horizontal courses—Defects of system—Batter undesirable—Stone facing—Breakwaters formed of blocks resting on base of mass-concrete—Monolithic system of construction—Methods of depositing concrete under water—Causes of failure—Concrete bag-work—Fraserburgh breakwater—Wave-breaker—Breakwaters of blocks laid in sloping courses—Advantages of system—Colombo, Mormugão, and Manora (Kurrachee) breakwaters—Large blocks used at Réunion—Mound breakwaters—Angles of slopes indicative of extent of exposure—Plymouth, Kingstown, Table Bay, and Portland breakwaters—Pitched slopes—Disturbance of rubble by wave-action—Holyhead breakwater—Madras breakwater—Sorting rubble for breakwater mounds—Cause of trouble at Plymouth breakwater—Alderney breakwater—Causes of failure—Mounds of pell-mell blocks on rubble bases—Mounds of rubble, faced and capped with pell-mell blocks—Mounds of pell-mell blocks, backed with rubble—Mounds of pell-mell blocks with superstructures—Rubble mound with pell-mell block facing and superstructure—Economy and advantages of using large blocks—General observations on rubble and concrete block mounds—Failures of pell-mell block breakwaters—Particulars relating to various pell-mell block breakwaters—Rubble mound breakwaters, faced and capped with stepped blocks in courses—Particulars of cost, rate of progress, maintenance, etc., of various existing breakwaters.

BREAKWATERS may be classed generally under two main heads, viz. the vertical type and the mound type.

Of the vertical type, which must be taken to include structures with "battered" or slightly inclined faces, we find—

1. Timber framing filled with rubble stone.

2. Outer walls, formed of masonry or concrete blocks (either laid "dry"[1] or in cement), with a hearting of "dry" rubble.

---

[1] Without mortar of any kind.

3. Concrete blocks, laid in horizontal courses, either throughout the structure or in conjunction with a hearting and base of mass-work.

4. Mass-work of concrete deposited within temporary frames.

5. The same, with a base formed of concrete deposited in bags.

6. Concrete blocks laid in sloping courses.

7. Any of the foregoing, with the addition of a wave-breaker of heavy blocks on the weather side.

Of the mound type we find—

1. Mounds formed of rubble stone of all sizes, thrown into the sea and allowed to take such slopes as the waves may give them. Such mounds may either be left with loose rubble faces as deposited, or the slopes may be faced with stone pitching, as has been done at Plymouth and Kingstown.

2. Mounds of concrete blocks thrown together pell-mell, sometimes associated with rubble, and brought up to the level of high water or a few feet above it. Of this type the breakwaters at Alexandria and Algiers are examples.

The combinations of the above-named types are almost infinite, indicating that in the construction of breakwaters, as in that of other engineering works, no one material or method of using it can be considered the best under all circumstances.

The vertical type of breakwater requires less material per unit of length—other things being equal—than any other form. It is, therefore, a proper section to adopt where suitable materials for breakwater construction are scarce or costly, provided that other conditions, such as excessive depth of water or a bad foundation, do not overrule its adoption.

Even where a foundation is questionable, if the depth of water is not too great, the structure may be carried upon pile-work (p. 272), or additional stability may be given by depositing a bed of rubble, as was done at Ymuiden and the Tyne. In either case, wide-spreading aprons should be provided to prevent scour and undermining.

With regard to the action of waves against a vertical face, waves of oscillation, and also those of translation up to certain limits, rise against such a face to approximately double the height of their crests above the normal water-level, and they are reflected from it, or from a face having a backward inclination, or batter, not exceeding 45 degrees.

A similar wave of depression is propagated downwards, which tends to scour out a hollow along the base of the work.

Waves which are eminently translatory throw their full weight against such surfaces, and expend their energy by raising columns of broken water to a great height.

In Chapter II., I endeavoured to show that in water which is not very deep in proportion to the length of waves—by which I mean any depth in which breakwaters have been, or are likely to be constructed—the higher and longer the waves are, the more is the element of translation developed in them.

It therefore follows that all great storm-waves, traversing water of such depth as to admit of breakwaters being constructed in it, are decidedly translatory; and it is thus evident that a vertical-faced work cannot be regarded as a charmer of such waves, however well it may reflect those of smaller dimensions. Hence we find vertical sea-cliffs being assailed with terrific violence, and scarcely a winter passes without our hearing of injury having been done to piers of the vertical type on different parts of the coast.

A vertical face, therefore, fails to uphold all the good qualities which are so often claimed for it, just at the time when a display of them would be most acceptable.

About a century ago Captain Cook reported—

> "At eight o'clock saw an island of ice to the westward of us, being then in latitude of 50° 40′ south, and longitude 2° 0′ east of the Cape of Good Hope. . . . I judged it to be about 50 feet high and half a mile in circuit. It was flat at the top, and its sides rose in a *perpendicular* direction, *against which the sea broke exceedingly high*. . . . In the evening we had three islands of ice in sight, all of them large; especially one, which was larger than any we have seen. The side opposed to us seemed to be a mile in extent; if so, it could not have been less than three in circuit. It could not be less than 100 feet high, *yet such was the impetuous force and height of the waves which were broken against it, by meeting with such a sudden resistance, that they rose considerably higher*."[1]

---

[1] "Voyage round the World." Quoted by Wright in "The Ice Age in North America," pp. 103, 104.

BREAKWATERS OF THE VERTICAL TYPE.

1. *Timber Framing filled with Rubble Stone.*

Where suitable materials can be procured at reasonable cost, pile-work breakwaters, with a hearting of rubble stone, may often be constructed quickly, and at considerably less cost than those built of solid masonry or concrete. Breakwaters of this class have been constructed at Great Yarmouth, Boulogne, Calais, Dieppe, Blyth, Dover (old harbour), Port Elizabeth, and many other places.

It may sometimes happen that the money available for harbour improvements is insufficient for the construction of what may be termed first-class works; but it may, nevertheless, if judiciously expended, be ample for works of a more temporary nature, which will afford the requisite facilities for a time, and possibly encourage trade and create a revenue, such as to admit of their being improved or extended later on. In such cases, breakwaters of the class we are now considering may often be adopted with advantage.

They are sometimes used for training the channels at the mouths of rivers, and are suitable for this purpose when the exposure is not great.

Piers of this type were constructed at the mouth of the river Wear upwards of one hundred years ago, and a portion of the pier at Calais is of similar age. In the case of the Wear breakwaters, the timber frames were put together on the land, in lengths of 30 feet. They were then launched into the river, and loaded with large stones to the extent requisite to give them stability; after which they were floated into position, and sunk on the sand at about low-water level. Additional braces and sills were then bolted on, and rubble filled in, the largest of the stones being selected for building the inner and outer faces of the pier.

Breakwaters of this class are best suited for shallow water, where they will not be exposed to very heavy seas.

When the ground is suitable, the piles for such breakwaters, instead of being framed together on land, as was done at the Wear, are generally driven from an overhanging travelling stage, the ties and bracings being fixed to them in place.

It is very necessary, in constructing such works, to back up the framework with rubble as quickly as possible, because upon this the stability of the structure in a great measure depends; and frames, while unbacked, are very liable to be displaced and damaged, even by moderate seas.

The function of the timber-framing is to encase the rubble and prevent its dispersion, the rubble, in its turn, giving support to the framing by its weight.

The larger stones, selected for the faces, are usually packed in their rough undressed state, so as to form fairly close work, the largest, as a matter of course, being reserved for the weather side. The hearting is usually formed by merely tipping the rubble from waggons.

Some years ago, acting under the late Sir John Coode's instructions, I removed one of these breakwaters, which was constructed between the years 1856 to 1865. It was 1300 feet in length, and originally extended into water having a depth of 23 feet at L.W.O.S.T. It was exposed to heavy seas, which it withstood remarkably well. Unfortunately, it was so placed as to act the part of a groyne, and cause considerable shoaling; hence the necessity for its removal.

The ties and braces in this structure were formed of double-headed iron rails, weighing about 84 lbs. per lineal yard, and they passed completely through the work. Similar rails were also used as outer walings.

After a lapse of about twenty-three years, although the rails were thickly encrusted with rust, they were quite sound, and had lost very little of their weight.

The piles of this breakwater were of ironwood, and were for the most part completely eaten through by sea-worms at about the level of low water of neap tides. Notwithstanding this, the rail ties, above and below that level, held the frame timbers together so well that the upper portion of the framework remained like a cap placed over the rubble.

The methods adopted for repairing breakwaters of this description necessarily vary under different conditions. If the nature of the bottom will admit of it, the driving of an outer row of piles is sometimes resorted to.

In some cases, when the piles have decayed, the structures have been encased with concrete blocks. In other instances the timber-work has been renewed pile by pile, or piece by piece, as it became decayed.

In designing works of this class, facility of repair should be kept prominently in view; and inaccessible parts, such as bracings and through ties, should be made of the most durable materials, as in the case of the breakwater just referred to. A typical drawing of a timber-framed rubble breakwater is given in Fig. 28.

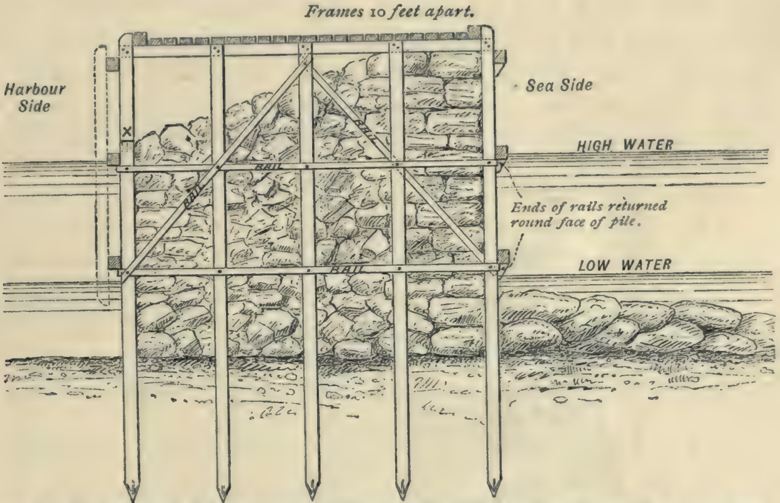


FIG. 28.—Type section of timber-framed breakwater with rubble hearting. Intermediate piles, spaced 2 feet 6 inches centre to centre, carried to full height on seaward side, and up to the level indicated at X on harbour side.

The description of timber to be used for the piles, etc., will depend much upon the presence, or otherwise, of sea-worms in the locality, reference to which was made in Chapter VII., Section 5, p. 131.

2. *Breakwaters with Side Walls of Concrete Blocks or Masonry, and Hearting of Dry Rubble.*

This class of breakwater, like the one we have just been considering, is only suitable for sites where the exposure is small. In some such situations, especially where extra width is required for quay space, it may be adopted with advantage.

Examples of breakwaters of this type may be seen at Peterhead (old harbours), Whitehaven, Kilrush, Seaham, and many other places.

The Kilrush pier, a section of which is given on the next page (Fig. 29), is a good example of this class of work.

The ill-fated breakwater at Wick, which occupied a very exposed position, was of a somewhat similar design. When inspecting its ruins a few years ago, I was informed, by one who had witnessed its destruction, that the inner or harbour wall was the first to give way, it having been thrust out by the weight of water falling upon the roadway. The outer or sea wall stood for some time after the harbour wall had succumbed; but, on the rubble hearting being ploughed out by successive seas, it lost its support, and was overturned by the force of the waves.

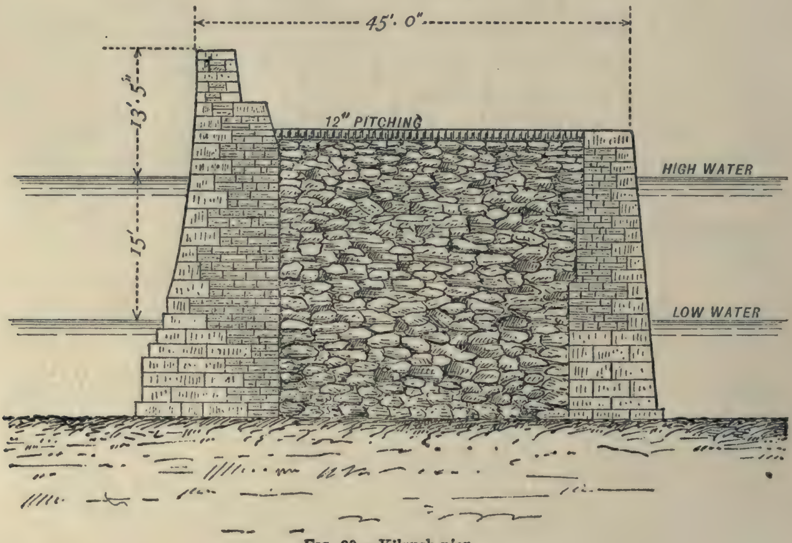


Fig. 29.—Kilrush pier.

The failure of the St. Heliers (Jersey) landing-pier was, in a great measure, due to the same cause.

Exceptional risk is incurred during the construction of breakwaters of this description. The side walls are advanced, and have to stand unsupported until the rubble is filled in between them, as far as the cross-walls—placed, it may be, about 30 feet apart—will admit. This having been done, a heavy gale probably occurs before the rubble can be protected, and the cavities are all filled with water. Upon this the masses of water which are thrown up by waves striking the face fall, and the resulting pressure, acting like a force-pump, bursts the work asunder, as just described.

Obviously, the roadway of such a breakwater as this should be made exceptionally strong, because during a storm it may be regarded as the key to the whole position.

On the other hand, if it be made air-tight, and the joints on the seaward face of the breakwater be left open, as they too often are, it may be blown up by the stroke of the waves upon the face of the work; or it may even conduce to the injury of other portions of the work, by preventing the free escape of pent-up air and water.

There can be little doubt that loose rubble hearting is a thing to be avoided, excepting under very favourable conditions.

Advantages of using Large Concrete Blocks in Breakwater Construction.

The employment of large blocks of concrete in constructing breakwaters possesses many advantages over the old system of building with rubble or blocked stone in place. Each individual block is, by virtue of its weight, far better able to resist heavy seas than newly built masonry composed of smaller materials; and, seeing that the setting of a large block occupies very little more time than is required for the setting of a smaller one, the work can be rapidly brought up when once the bottom course has been properly laid, it being thus possible to utilize fine weather to the fullest extent.

The making of blocks may also be proceeded with concurrently with the building of the breakwater, as well as during rough weather, when building in the sea is impossible. The workmen, when not engaged on the breakwater, may thus be profitably employed in the workyard, making blocks ready for setting when the weather will permit.

In building blocks in the block-yard, unharassed by tides and waves, the work can be done in a more perfect and solid manner than is possible in a tideway; and, seeing that they are, or should be, allowed ample time to harden before being put into the sea, the risks inseparable from newly built work in the sea are much reduced.

3. *Breakwaters formed of Concrete Blocks laid in Horizontal Courses.*

In this class of breakwater—illustrated in Fig. 30—the preparation, and especially the levelling, of the foundation to receive the bottom course of blocks requires to be done with very great care. This having been satisfactorily accomplished, the blocks are lowered by the setting-machine, and placed in position by the aid of divers. Those below low water are of necessity laid "dry"—that is to say, without cement or other adjusting medium between them, such as a bed of mortar would afford—and this, unfortunately, constitutes a serious defect, seeing that, unless the surfaces are perfectly true, and the blocks laid in precisely the same plane (which can never be the case in practice), they bear upon each other on points and edges only, which is apt to cause breakage of the blocks and dislocation of the work (see p. 244).

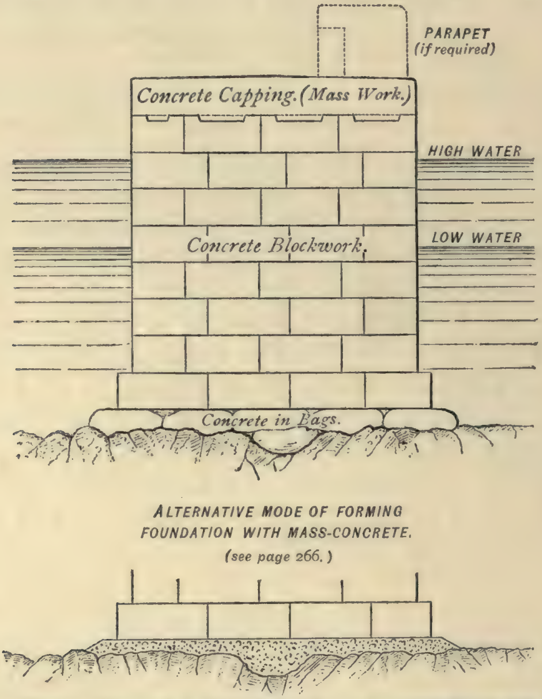


Fig. 30.—Type section of breakwater formed of concrete blocks laid in horizontal courses.

The difficulty is increased if unequal settlement should take place, or if several courses have to be laid, in this manner, one upon the other; indeed, sometimes the unevenness is such that the block surfaces have to be pick-dressed and levelled by mason-divers as the work proceeds, an operation which entails much expense and loss of time.

At the low-water course bedding the blocks in cement is commonly commenced; and it is here where delay so often takes place, while waiting for the coincidence of spring tides and fine weather to enable the work to be proceeded with.

This trouble is the same whether the base for the low-water course is of blocks or of mass-concrete, and it is largely owing to the difficulties which are experienced at this stage of the work that the construction of breakwaters of this and similar types in exposed situations often proves so tedious and costly.

When the upper courses have been satisfactorily set in cement and grouted, they are practically monolithic.

The blocks of the top course may with advantage be moulded with sinkages, similar to the "frogs" in bricks. This gives the capping an additional hold, and also ties the blocks together.

The capping is commonly formed of mass-concrete deposited in place; and, with the view of preventing unsightly cracks, it should be moulded in short lengths, each length covering not more than two, or at the most three, rows of blocks.

A breakwater constructed in the manner just described should have an unexceptionable foundation, otherwise unequal settlement is almost sure to occur, resulting in manifold evils. The "Titan," or setting-machine (assuming such to be used), as it advances upon each succeeding length of the new work, is often responsible for a good deal of trouble in this respect.[1] Furthermore, should local settlement take place, the dry-set blocks are liable to fall away from the top monolithic work, and when thus relieved of weight they are easily drawn out by the waves, thus causing serious damage to the work—as experience has often shown (see Fig. 31, p. 182).

In these respects, as in others, the sloping-block system, which will be shortly described, possesses many advantages, one point especially in its favour being that during construction the work is to a great extent independent of the tides.

All bags of concrete used in levelling up foundations should, where practicable, be laid athwart the breakwater, and the interstices should be filled and carefully levelled by means of smaller bags containing specially soft, rich concrete, or with similar concrete deposited in mass (see pp. 266 *et seq.*).

---

[1] The "Titan" at Colombo, which in working order weighed 180 tons, caused a settlement of from 3 to 5 inches in passing over new work (*Min. Proc. Inst. C.E.*, vol. lxxxvii. p. 82).

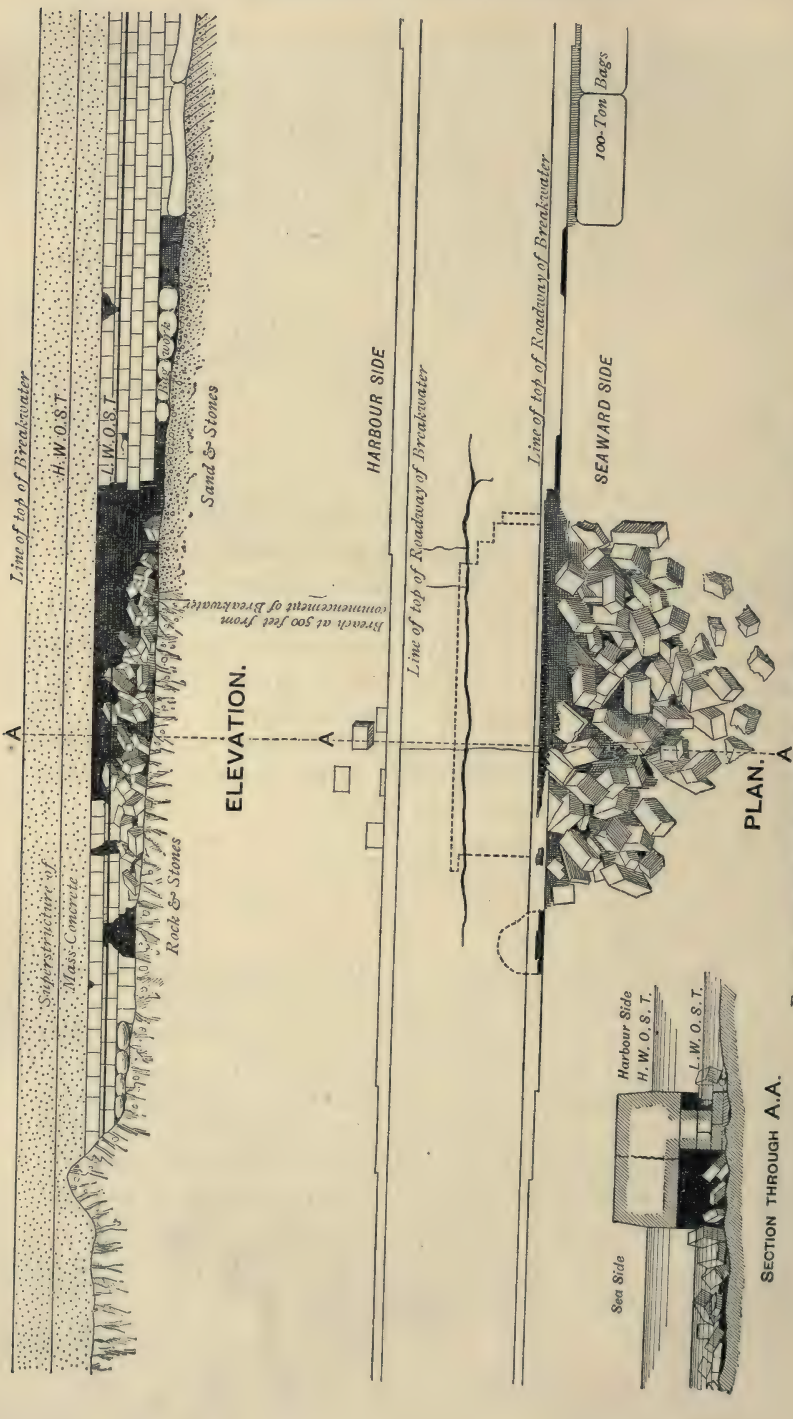

Line of top of Breakwater
H.W.O.S.T
L.W.O.S.T
Superstructure of Mass-Concrete
Bag work
Sand & Stones
Rock & Stones
Breach at 500 feet from commencement of Breakwater
A
ELEVATION.
A
HARBOUR SIDE
Line of top of Roadway of Breakwater
Line of top of Roadway of Breakwater
SEAWARD SIDE
100-Ton Bags
A
PLAN.
Harbour Side
H. W. O. S. T.
L. W. O. S. T.
Sea Side
SECTION THROUGH A.A.

FIG. 31.—Aberdeen south breakwater. Plan showing damage caused by storm.[1]

---

[1] Copied by permission from a drawing illustrating a report by Mr. Wm. Smith, M. Inst. C.E., 1883.

All blocks should be laid as "headers." The smallest possible surface will thus be opposed to the wave-stroke, the "scar end"[1] of the work will be shortened, and the blocks will be less liable to fracture by settlement than when "stretchers" are introduced.

Batter in the faces of piers is objectionable, inasmuch as it relieves the outer blocks of the lower courses from weight, and necessitates a larger number of different-sized blocks being made than would otherwise be required, thus involving extra expense for moulds, etc.

If desired, the outside blocks may be faced with stone on their exposed faces, so as to enable them the better to resist erosion. In such cases the stones should be properly bonded and built into the block faces at the time the blocks are being made, care being taken to ensure full beds and joints and a perfect union with the concrete.

A form of breakwater which has several points to recommend it, especially for small or moderate depths of water, and where the foundation is good, is one in which a base of mass-work is brought up to slightly above the level of low water of neap tides, the remainder of the work being carried up with concrete blocks set in cement. By this arrangement the work may be quickly raised above high water, and the risks inseparable from the putting in of mass-work within the tidal range be to some extent avoided.

A type drawing of this form of breakwater will be found in Fig. 32, p. 184.

4. *Breakwaters or Piers of Concrete Mass-work, deposited within Temporary Frames.*

The monolithic system, already referred to, or that of forming breakwaters by depositing freshly mixed concrete within temporary timber frames, either under or above the water-level, is applicable to large and small works alike, and may, if necessary, be carried out with a very small expenditure on plant; whereas, if the magnitude of the work is such as to warrant the use of plant on a larger scale, the rate of progress may be correspondingly increased, and the cost of the work diminished.

By this system the tedious and expensive operation of accurately levelling foundations is to a great extent rendered unnecessary, and large monolithic blocks may be constructed

---

[1] The free end of a breakwater during construction.

in situ, so that all the advantages which such masses afford, in stability and otherwise, are secured without its being necessary to provide costly plant for dealing with such loads. Indeed, monolithic blocks are often made of such weight that no lifting appliances, in reason, could cope with them.

The system is not, however, without serious drawbacks. It is essentially a fine-weather method of constructing work, and those who adopt it must be prepared for interruptions and losses, arising alike from injury to the frames and to the soft concrete deposited within them, the frames being specially liable to derangement before the concrete is put into them.

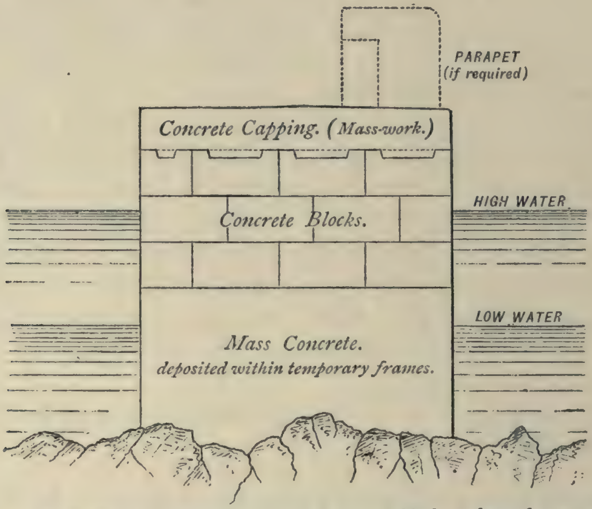


FIG. 32.—Type section of breakwater formed of concrete blocks on base of mass-work.

When depositing concrete under water, very great care is necessary to prevent loss of cement.

The method usually adopted in constructing this class of work is to erect a framing of wood or iron, consisting of uprights, the ends of which rest either in shoes, or, if the sea-bed is of rock, in holes drilled therein, to which horizontal bars or wales are attached. To these are fixed planks, usually from 3 to 4 inches thick, which form the sides of the frame. The lower ends of these rest upon the sea-bed, or other base, and conform to any irregularities which may exist.

In cases where the foundation is very irregular, it may be necessary to cut the bottoms of the planks to fit it; but, should the openings not be too large, the canvas lining referred to below will be sufficient to prevent the escape of the concrete. Should the rock surface slope quickly, it may be necessary to bench it by blasting or otherwise.

The sides of the casing should be supported by means of through cross-ties (usually ¾-inch round iron), in order to prevent bulging by the lateral thrust of the liquid concrete; and, in order to prevent loss of cement by the wash of the sea, the sides and a portion of the bottom of the casing should be lined with strong jute canvas, secured to the planks by clout nails. Should the bottom be porous, as would be the case in founding upon a rubble base, its entire surface should be covered with canvas; indeed, in such a case a large bag, made to loosely fit the casing, should be used.

The frames are frequently anchored to the bottom by means of stay chains attached to lewises, union screws being provided for tightening them up.

After the concrete has been deposited, its surface, if within reach of the waves, should be protected from their fretting action by one or other of the methods described on pp. 258 and 259.

In founding upon a level base, the frames may be used over and over again; but when the ground is uneven it is often necessary to cut timber for each frame, the cost of the work being thus increased, not only by the unavoidable waste of timber, but also by the extra labour entailed.[1]

Furthermore, it is necessary to use a larger proportion of cement in concrete which is deposited under water in this manner than in blocks which are made and allowed to harden before being put into the sea, the cost of the work being thus still further increased.

The difficulty of usefully employing men engaged on this class of work when it is interrupted, either by rough weather or in some other way, is not the least of its drawbacks, and in this respect it contrasts unfavourably with the block system of construction.

From what has been said, it will be seen that work performed in this way in an exposed situation may prove very costly, especially when it happens to be below low water, and divers have to be employed.

[1] When the foundation is fairly level, horizonal boarding is sometimes used in preference to vertical.

A convenient way of depositing the concrete is to fill it into skips having hinged flap bottoms. The skips are then lifted by a crane and swung over the site where the concrete has to be lodged. They should be lowered to within a short distance of the bottom, only sufficient room being left for the flaps to swing open. On the catch being released—which is usually done by means of a small chain from above—the contents of the skip are discharged. The skip should then be withdrawn from the water slowly and steadily, every precaution being taken to avoid disturbance of the cement.

The practice, sometimes adopted, of sending a diver down into the frame to level the concrete is objectionable, and is calculated to do more harm than good, inasmuch as the cement, if stirred up in the water, either loses its setting properties, or is washed out and lost.

With the exercise of due care in regard to the position of the skips, and the occasional use of a sounding-pole, concrete may be deposited with sufficient regularity within the frame to obviate the necessity for any manipulation until its surface has been raised above the water-level.

Sometimes mass concrete is deposited under water by passing it through a shoot or trunk. In order to exclude the water, the shoot should be kept full of concrete by filling it in continuously at the top. It should extend nearly to the bottom, and it ought to be slowly moved about so as to distribute the concrete. The system of depositing concrete by means of skips is, however, generally preferred. A system which I have found successful, and which I believe I may claim to have originated, is that of lowering concrete through water in bags of convenient size, mouth downwards. Those I have used contained about 2¼ cubic feet of concrete apiece, but, if desired, they could, of course, be made to contain much more.

The system will be more fully described when treating of rock foundations (pp. 267 *et seq.*).

In order to avoid the formation of cleavage surfaces, it is of importance that the deposit of concrete should be as continuous as possible.

Very good work may be done on the monolithic system, but so much depends upon the care with which it is executed, that it entails a considerable element of risk. It has been largely used both above and below water, and is generally applicable in moderate depths, say to 10 or 15 feet below low water. A type section of this class of breakwater will be found in Fig. 35, p. 192.

Although in principle the system is a good one, there have been many failures in works where it has been adopted; but they may nearly all be attributed either to too small a proportion of cement having been used in the concrete, or to the use of cement of inferior quality, with which I couple cement which has not been properly aërated or slaked.

Every endeavour should be made to ensure the faces of the work being as good and impermeable as possible.

Large pieces of clean stone may, from motives of economy, be incorporated in mass concrete if desired. These should not be allowed to touch each other, but should be kept at least 9 inches or 1 foot apart. They should only be deposited where there is a sufficient mass of concrete to ensure not only a good bed and bond, but also a partial submergence in it.

In under-water work, experience seems to indicate that the proportion of stone incorporated in this manner should not exceed one-sixth of the entire mass; some engineers consider it undesirable to use any. Above water, as much as one-third or even more may be used.

For under-water mass-work many engineers use concrete as rich as 1 part of cement to 3 or 4 parts of shingle. In some positions this is no doubt desirable; in others it might appear somewhat extravagant. It has, however, been demonstrated in several works that mass-work, even above water, made of concrete composed of 8 or 9 parts of shingle to 1 part of Portland cement has not sufficient strength for sea-work, it having, in numerous instances, been eroded and disintegrated, in a very short space of time, by the impact of the waves and the chemical action of the sea-water.

Monolithic work should be executed in sections of convenient length, say from 15 feet to 20 feet, each section terminating with a vertical joint. If this precaution be not taken, irregular cracks will make their appearance and break up the work in an unsightly, if not in an injurious, manner.

Mr. B. B. Stoney, M. Inst. C.E., has suggested a mode of forming breakwaters by constructing very large blocks of concrete—say 300 tons in weight—in some sheltered position, commanded by powerful floating shears, by means of which they would be lifted and conveyed to the site of the breakwater, and there be set in position. This system was successfully adopted by him in constructing river walls in the Liffey at Dublin; but the operation would be attended with much more difficulty and risk in the open sea.

No doubt, a breakwater constructed in this manner could be made very stable; but in exposed situations the number of working days would be very small, and the cost of plant would be too large to admit of the system being adopted in any but very large undertakings.

This mode of constructing breakwaters scarcely belongs to the monolithic system, but, in regard to size of blocks, it is akin to it.

5. *Concrete Bag-work.*

Concrete placed in strong bags made of jute sacking, and deposited while in a soft state, may be conveniently applied in forming under-water foundations and the bases of piers. By this method, inequalities, especially in crossing rocky ground, may be readily adjusted, and a fairly level bed be obtained upon which to raise a superstructure.

Where bags, or "bag-blocks," as they are sometimes called, of large size are used, the spaces between them may be filled up and levelled with rich concrete deposited in the manner described on pp. 266 *et seq.*, or smaller bags may be used, in which case they should be placed and well packed in by divers.

Bags of large size are often used in forming "aprons" to protect foundations from disturbance by scour. They conform very closely to the irregularities of the surface, and so bind together the loose stones or rubble upon which they rest. This quality gives bag-work a special value when applied to "aprons," or in other situations subject to much disturbance.

The bags are commonly deposited by means of iron skips of special construction, having their bottoms formed of flaps or lids opening outwards and supported by catches, as shown in Fig. 33.

These skips may be of almost any capacity, but they generally range from about 5 tons to 20 tons.

In constructing the breakwater at Newhaven (Sussex), bag-blocks weighing 100 tons each were deposited by means of a steam hopper barge, the concrete for filling one of these being mixed in about 20 minutes by a large "Carey-Latham" machine.

Large bag-blocks were, I believe, first used by Mr. Dyce Cay, M. Inst. C.E., in constructing the Aberdeen breakwaters. Some of these, which form the "apron" on the seaward side of the south breakwater, weigh about 100 tons each. They were dropped a distance of from 40 feet to 50 feet from a movable hopper box, bracketed out from the side of the breakwater, there being no machine upon the works available for depositing them otherwise. In the north breakwater they were placed by means of a hopper barge, which was afterwards used for similar work at Fraserburgh.

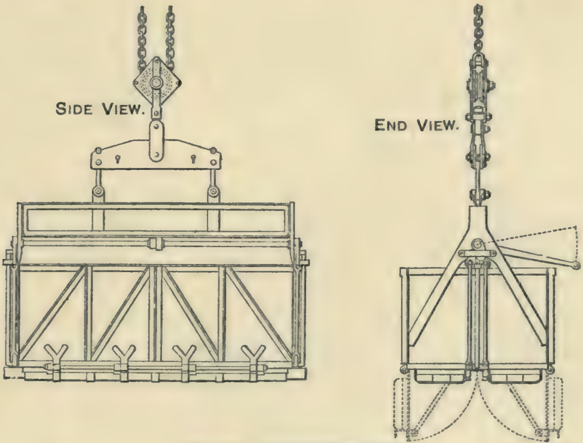


FIG. 33.—Concrete bag-box.[1]

It is important that concrete in bag-work should be deposited in place as soon after mixing as possible, otherwise setting commences, any interference with which impairs the strength of the concrete, rendering it friable and very liable to disintegrate.

In placing bag-blocks under water, the box should be lowered over the site where the bag is to be deposited, only sufficient room being allowed, as in the case of mass-work, to give clearance for the box flaps to open. The distance through which the bags have to fall is thus reduced to a minimum, and the rending of the canvas by the weight of the concrete, which sometimes occurs, is obviated.

The system of dropping large bags of concrete through a considerable depth of water is injurious, and should be discouraged as much as possible. Several years ago I inspected a mound of bag-work which was being deposited from hopper barges in this manner, and I noticed that the bags were much broken, the mound presenting somewhat the appearance of a shingle beach, in consequence of the sea having washed out the cement and dispersed much of the shingle of which the concrete was composed.

---

[1] *Min. Proc. Inst. C.E.*, vol. cxiii.

When a box containing a bag-block has been lowered to within a short distance of the bottom, its position should be adjusted by divers—unless some other means can be devised—so that the bag may, on the catch being released, fall into the place assigned for it.

The canvas, which in large bags is sometimes used double, or strengthened by means of belts of the same material, effectually prevents the cement from being washed out by the action of the sea, unless broken by rough usage.

Bag-work may be roughly levelled at the time of deposit, by the divers using "beaters," or preferably by weight applied from above, in obedience to the divers' signals. Squeezing by application of weight is better than beating, but as little of either should be resorted to as possible.

On no account should concrete be meddled with when once it has commenced to set, until it has become sufficiently hard to admit of being dressed off by picks, without injury to that which remains. This may be done before the concrete is so hard as to entail much labour.

Bags should be made slightly larger than the boxes, so as to give the concrete, when deposited, freedom to spread and conform to irregularities of the bottom, and also to allow for the shrinkage[1] of the canvas when wetted. The amount of slackness to be given will vary according to the proportions of the bags, shallow bags requiring less in proportion than deeper ones, on account of the concrete having less tendency to spread. The correct amount to allow is best ascertained by experiment.

The proportions of materials most suitable for making concrete to be used in this class of work are 1 part of Portland cement to 4 or 5 parts of sand and shingle or broken stone. The proportion of sand relatively to the stone or shingle should be rather more than is used for work above water, and the concrete should be mixed rather wetter. The shingle should not be too coarse, and the stone should be broken extra small.

---

[1] This varies in different qualities of canvas. It is very small in the direction of the "weft," or from selvedge to selvedge, but in ordinary jute sacking it amounts, on an average, to somewhat under half an inch in a foot along the "warp," or in the direction of the length of the piece.

Fig. 34 illustrates a frame for depositing concrete bags which I designed with the view of enabling divers to make closer and more regular work than is possible when bags are dropped out of boxes in the ordinary way.

Bags for use with these frames are provided with bands or girths, terminating in tabs, in each of which an eyelet-hole is worked. The bags, when being filled, are placed in rectangular boxes which have movable sides. When a bag is full it is sewn up, and the frame is placed upon it. The tabs are then hitched upon the side hooks, and the sides of the box released by knocking up a catch, the bag being then ready for lifting and placing. The bags retain, in a somewhat remarkable manner, their rectangular form, even when they contain very soft concrete; and divers are able to make very close work with bags deposited by means of frames in this manner. After a bag has been placed in position the tabs are unhooked, and the frame is thus released. The tabs, being of no further use, are usually cut off.

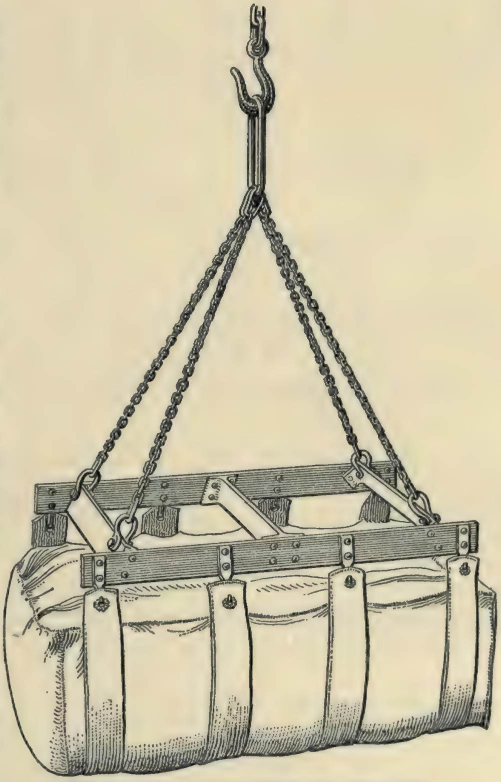


Fig. 34.—Frame for depositing bags of concrete.

The breaking weight of a four-ply band, 5 inches wide, of good jute sacking, such as cement-bags are generally made of, is about 10 cwt.; so, allowing a proper margin of safety for working loads, the number of bands required to carry a bag of concrete of any given weight can be readily determined. Thus, assuming the bands in the illustration to be of the dimensions named, they would just break with a load of four tons.

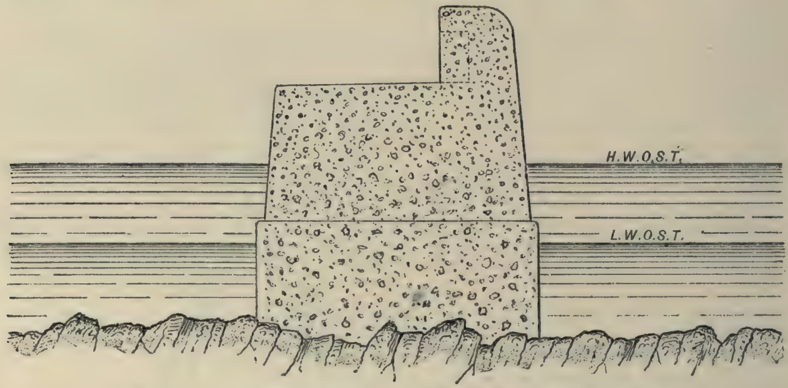


Fig. 35.—Type section of breakwater formed entirely of mass concrete.

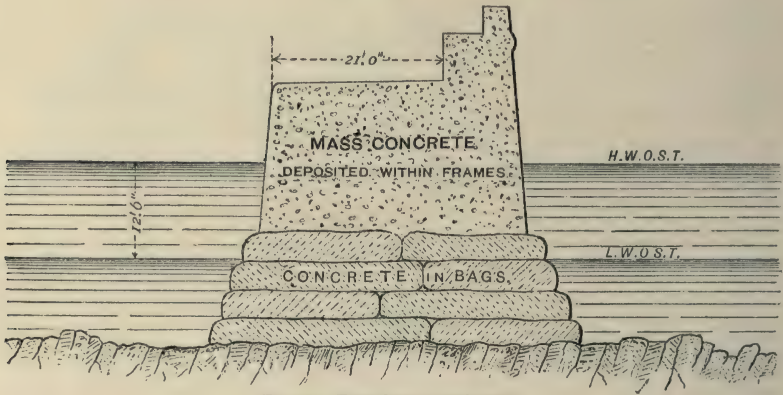


Fig. 36.—Fraserburgh breakwater.

In Fig. 35 a type section of breakwater is shown constructed entirely on the monolithic system. Fig. 36 shows a section of the breakwater at Fraserburgh, which was constructed on the same system, but with a base of bag-work.

Inasmuch as it is almost impossible to avoid leaving some spaces between the bags in bag-work, especially at their ends, it is not desirable to expose a bag-work face to the stroke of very heavy waves. This class of work is therefore best adapted for sites of small or moderate exposure, or for foundations well below the low-water level.

If protected by a wave-breaker on the weather side, as shown in Fig. 37, bag-work may, however, in some cases be brought up to or above the level of low water with advantage; but, should it be intended to use the breakwater as a quay, the projecting ends of the bags on the harbour side would be found inconvenient.

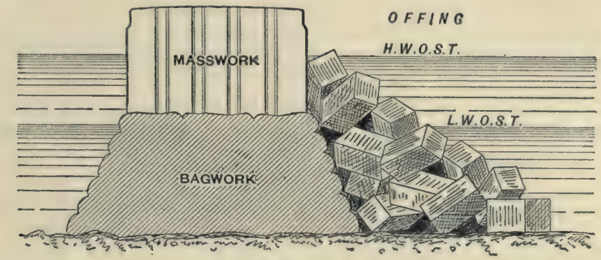


FIG. 37.—Type section of breakwater with bag-work base, mass-work superstructure, and pell-mell block wave-breaker.

A monolithic pier has lately been constructed at Skinninggrove, on the Yorkshire coast. In this pier the concrete forming the base, instead of being confined within temporary frames, was deposited in its loose state, and allowed to take its natural slope.

The depth at low water springs was 6 feet, and the concrete used was of the following proportions: 2½ parts of broken slag of varying size, ½ part of rough gravel, 1 part of sand, 1 part of slag cement.

It is stated that the loss of concrete due to rough weather was very small. The slope on the harbour side was cut away after the concrete had become hard, in order to enable vessels to lie alongside of the pier.[1]

6. *Breakwaters of Concrete Blocks, laid in Sloping Courses.*

Sloping-coursed work—in which the blocks or stones are set on edge, after the fashion of steeply inclined beds of stratified rock—is very suitable for breakwaters, either of the purely vertical type or in combination with a rubble base.

---

[1] *Engineering*, vol. liv. p. 456.

Irregularities in the foundations can be readily levelled up by the use of concrete in mass or in bags, or by broken stone, according to the depth of water and exposure of the site; and inequalities at the quay-level may be adjusted by means of a capping of mass-work, similar to that represented in Figs. 30, 32, pp. 180, 184.

Rapid progress may be made with work constructed on this principle, and the scar-end[1] can be easily and effectually secured against heavy seas. It may, moreover, be made much shorter in proportion to its height than is possible with horizontal courses; consequently the machine used for setting the blocks need not have so great an overhang, and its cost and weight will, as a matter of course, be proportionately reduced.

The setting machine, or "Titan," used in constructing the Colombo breakwater, on the above system, was adapted for lifting loads up to 40 tons, and it had an overhang of 28 feet. That at Mormugão was of somewhat similar design, and was adapted for dealing with loads up to 45 tons, its overhang being about 25 feet.

Blocks weighing 27 tons each were employed in constructing the Manora breakwater (Kurrachee), which is also built on the sloping-block system. The machine used for setting these was almost identical with the one used at Mormugão, but its overhang was slightly less.

The inclination of the blocks in this breakwater was 1 in 4 (about 76°).

At Réunion harbour, where the same method of construction was adopted, blocks weighing as much as 113 tons each were placed in the work at a short overhang, and others weighing 40 tons each were laid at an overhang of about 42 feet.

In illustration of this system of construction, sections and part elevations of the Colombo and Mormugão breakwaters are given in Fig. 38 and 39. They are, as will be seen, composite structures; but, omitting the rubble bases, they furnish good examples of the type of breakwater we are now considering.

---

[1] The scar-end is almost always a vulnerable point. When the season's work is over, and before winter gales begin, every care should therefore be taken to secure the work by cramping or tying together several of the end blocks in each course (assuming the work to consist of blocks). Sometimes the stepping of the courses is temporarily built up with masonry in order to do away with the re-entering corners, and so present a more even surface to the waves.

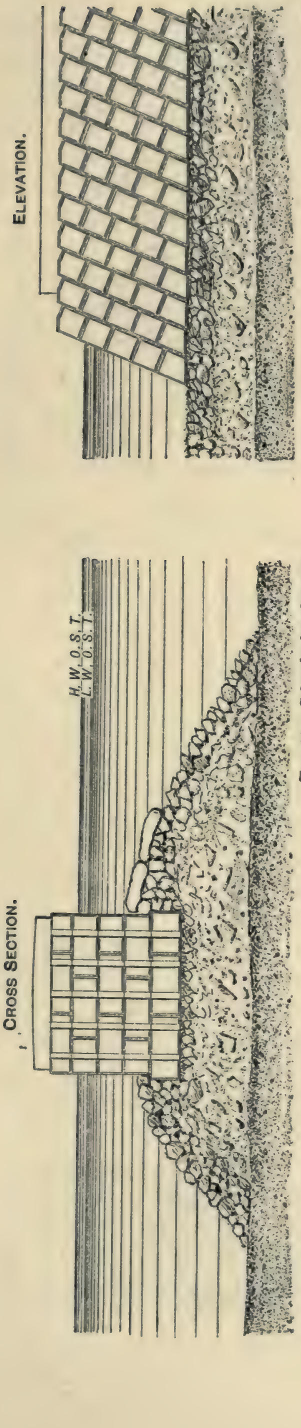


FIG. 38.—Colombo breakwater.

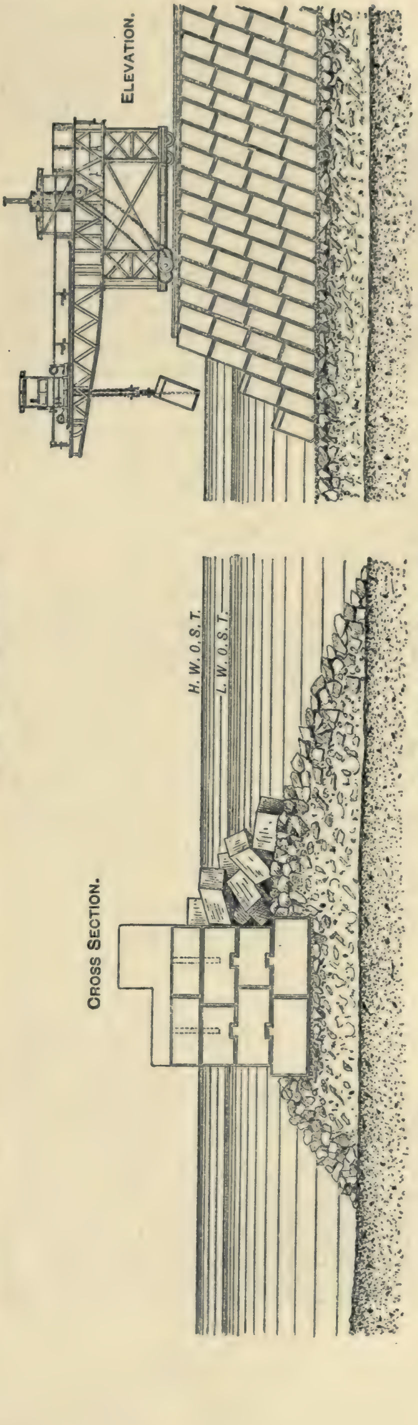


FIG. 39.—Mormugão breakwater.

The Colombo breakwater was designed by the late Sir John Coode, and was carried out under his direction by Mr. J. Kyle, M. Inst. C.E. That at Mormugão was designed by Messrs. Hawkshaw, Son, and Hayter, Mr. E. Sawyer, M. Inst. C.E., being the executive engineer.

In the latter work a wave-breaker, composed of 20-ton concrete blocks, was introduced, its object being to protect the toe of the superstructure from scour or undermining.

There is no wave-breaker to the Colombo breakwater, but the rubble at the toe of the upright work is protected by an apron, 24 feet wide, composed of 10-ton bags of concrete.

The wave-breaker at Mormugão appears, however, to have been more effective than the apron at Colombo, inasmuch as in the former case practically no expenditure has been incurred for maintenance, while at Colombo the mound foreshore has required a good deal of attention. The two sites, as regards exposure, etc., are very similar, as are also the main features of the breakwaters themselves.

All the blocks in the Colombo breakwater are bonded together, not only by "breaking joint" with each other, but also by means of joggles of large size, formed by filling grooves with concrete in bags, as indicated in Fig. 38, p. 195. There are five of these grooves in the width of the breakwater, and they extend continuously from top to bottom of each course of blocks. The blocks in this breakwater vary in weight from 16½ tons to 30 tons, and they are inclined at an angle of 68° to the horizon.

In the Mormugão breakwater tongues or projections on the top of the blocks, measuring 4 feet 6 inches wide by 2 feet 6 inches deep, and fitting into corresponding grooves or recesses in the superposed blocks, take the place of the joggle grooves, excepting in the uppermost blocks, which are dowelled to those below them by means of pieces of rail, this having been found more convenient than the tongues and grooves for purposes of alignment.

The blocks in the Mormugão breakwater weigh from 29 tons to 37½ tons each, and are set at an inclination of 70°, being almost the same as in the Colombo work.

In setting sloping blocks there is often a tendency for the toe of the work to outrun the top, or, in other words, for the slope to become flatter; but this may be easily rectified as the work advances by introducing compensating courses to the extent required. Every endeavour should, however, be made to prevent this flattening of the slope, and to ensure the courses being in close contact with each other throughout.[1]

This system of building sea-works has of late years been adopted for several important structures, and has attracted a good deal of attention. It is, however, by no means new. Sloping blocks of large stone were used at Ardrossan harbour, below low water, early in the present century. The old north pier at Aberdeen was constructed in this manner by Messrs. Telford and Gibb, in the year 1812; and the old east pier at Peterhead was similarly constructed by Telford about the year 1820.

For rapidity of construction, as well as for immunity from sea-risk during construction, and from injury resulting from settlement, this system compares very favourably with other methods of building breakwaters of the vertical type.

BREAKWATERS OF THE MOUND TYPE.

A. *Mound Breakwaters of Rubble Stone.*

It has already been stated (Chap. VIII.) that the materials readily available for a work must always largely influence an engineer in determining its design. This is, perhaps, in no case truer than when applied to the rubble mound type of breakwater, inasmuch as no engineer would think of suggesting such a design unless there were an abundant and easily accessible supply of suitable stone in the vicinity.

In the chapter on "Tides," it was shown to how great an extent breakwaters of this class are influenced by range of tide; it is, therefore, now only necessary to recall the fact to mind. Indeed, a perusal of Fig. 12, p. 59, will convey more information on the subject than anything further I could say.

A mound of rubble stone deposited in the sea will, ere long, be washed down by the action of the waves, and it will assume a profile which will vary in form in different localities, according to the height of the waves, the depth of the water, the size and specific gravity of the materials of which it is composed, and the level up to which it is carried in relation to the waterline. Such mounds form artificial boulder beaches, or sunken reefs, according to the level up to which they are brought; and they assume the forms which the laws of nature enforce, nothing more being necessary, in constructing a breakwater of this type, than to throw the stone into the sea, and allow the waves to do the rest of the work.

---

[1] This flattening of the slope is to some extent caused as follows: In heavy seas there is often a perceptible movement of the blocks, which, although it may be exceedingly small, is sufficient to make them rub and chafe one against the other. Small irregularities on their surfaces are thus ground off, and the blocks, pivoting on their bases, fall closer together. In construction, it is, moreover, impossible to make the lower blocks lean so hard against the previous course as the upper ones do.

The slopes of mounds which rise above low water, or in which the surface is not far below it, are often many years in coming to a state of rest, seeing that each storm greater than those preceding it draws down the material, and causes it to assume a flatter slope for a greater depth.

The sudden change which takes place in the slope of a mound on its weather side, at a level varying from about 10 feet to 15 feet below low water of spring tides, indicates very clearly the depth to which storm-waves have power to disturb the rubble, seeing that below this depth the material assumes a slope nearly corresponding with its natural angle of repose, say 1 in 1, or 1 in 1¼; whereas above that point, and up to the level of high water, the slope is very much flatter—being, in the Holyhead breakwater, as flat as 1 in 12 (Fig. 41).

Other things being equal, the form which the action of storm-waves imparts to the rubble in breakwaters of this class affords a reliable means of judging of the relative exposure of their sites.

Plymouth, Kingstown, and Table Bay breakwaters, also the outer portion of the one at Portland, are examples of mound breakwaters without superstructures.

At Plymouth and Kingstown the slopes are faced with heavy stone pitching down to low water of spring tides; they are not, therefore, liable to much disturbance above that level. Below low water, the rubble in the Plymouth breakwater has taken a slope which varies from 1 in 3¼ to 1 in 5 to a depth of about 10 feet, and from 1 in 1¼ to 1 in 1½ from that level to the bottom. There is an almost level benching, between 80 feet and 90 feet wide, which extends seaward from the toe of the pitched slope at about the low-water level. The inclination of the pitched slope on the weather side is 1 in 5, and on the harbour side, 1 in 1½.

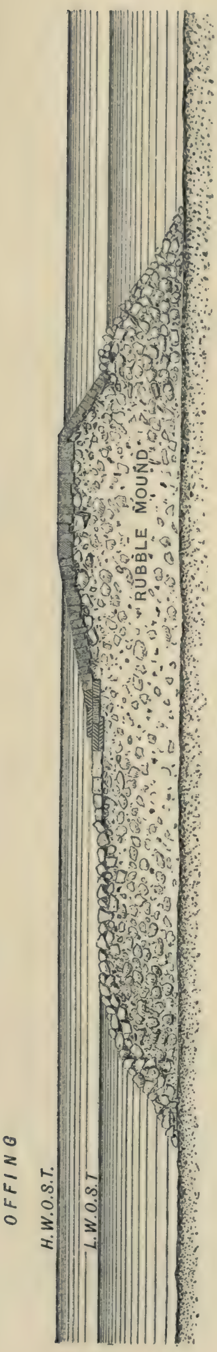


Fig. 40.—Plymouth breakwater.

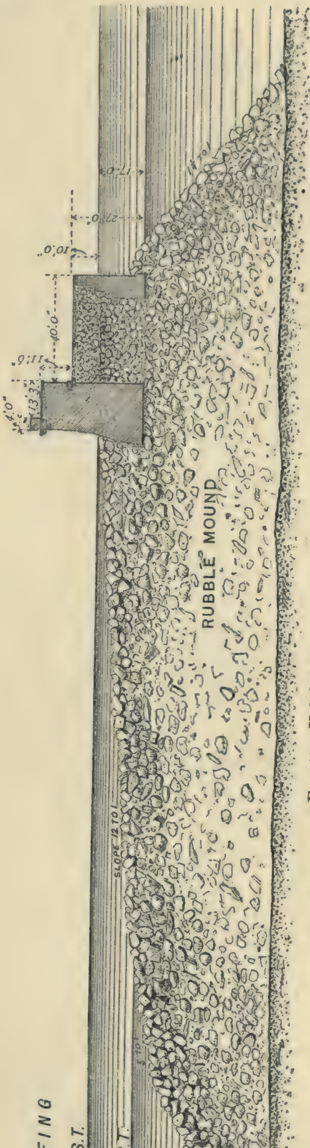


Fig. 41.—Holyhead breakwater.

These slopes were pitched with the view of putting a stop to the disturbance of the rubble; but the smooth face of the pitching on the seaward side so increased the effect of the drawback of the waves that the rubble at the toe of the pitching, or just about the low-water level, was disturbed by it more than ever. This caused a great deal of trouble, and necessitated the formation of a masonry toe composed of large carefully worked blocks of granite, dovetailed into each other so as to increase their stability.[1]

The return water down the slope tripped up the oncoming waves, and caused them to break more heavily upon the slope than they would otherwise have done. A section of this breakwater will be found in Fig. 40.

The seaward slopes of Table Bay breakwater are approximately 1 in 2½ from the top, which is 15 feet above high water of spring tides, to the level of high water. From high water to low water, 1 in 5; from low water to 15 feet below that level, 1 in 7; and thence to the bottom, 1 in 1½. The slopes upon the harbour side are 1 in 2 from the top to 5 feet below low water; and thence to the bottom they are 1 in 1½. The width at the level of high water is 110 feet.

It is worthy of note that the slopes of this breakwater, as formed by the severe gale which occurred in the year 1865, remained practically undisturbed for 24 years, or until the gale which occurred on July 30, 1889. This gale, however, further pulled down the rubble and flattened the slopes to the inclinations above stated.

In order to obviate the inconvenience of stone being thrown over the crest of this breakwater into the harbour during storms, a wall or "backbone" of concrete has recently been constructed along it.

An objection often urged against rubble mound breakwaters is, that the stones of which they are composed are subject to the same wear from wave-action as those which form boulder and shingle beaches. No doubt the surface stones are rolled about and rounded by the ceaseless action of the waves, and by their grinding one against the other, just as in the case of natural beaches; but the annual waste from this cause, even in such a large breakwater as that at Holyhead, is very small.

It is unreasonable to expect that works, especially sea-works, can be made to last for ever without maintenance; and such splendid examples of rubble mound breakwaters as at present exist show conclusively that works of this class may be maintained at a moderate cost, and that in this respect they do not compare unfavourably with many breakwaters of the vertical type (see pp. 216, *et seq.*).

---

[1] The pitching has now been extended over the benching so as to form an apron.

At depths varying from about 12 feet to 15 feet below low water of spring tides, a mound composed of rubble of comparatively small size — say stones of from 10 cwt. upwards—will remain undisturbed in heavy seas, *if no superstructure be placed upon it.*

During the construction of the Alderney breakwater, the rubble which was deposited to form the mound was allowed three years to consolidate before putting the superstructure upon it, and it was found that the heavy winter storms did not disturb it below the level of 15 feet below low water of spring tides.

The placing of a vertical structure upon a rubble mound, however, at once alters the pre-existing conditions, and, where no disturbance previously occurred, an excavating action will be found to come into play. This is caused by the downward action of the waves playing against the face of the wall, and by the force of their recoil, which was so great at Alderney that it ploughed out the mound to a depth of 20 feet below low water for a distance of from 80 to 90 feet from the face of the wall.

In the mound of the Colombo breakwater, stones weighing three tons and upwards were disturbed at depths varying from 10 to 14 feet below low water, and that by waves which never exceeded 15 feet in height.

At Port Elizabeth, some rubble was deposited at the head of the north jetty in order to protect it from scour. The depth at low water was 22 feet,[1] and the layer of stone was 3 feet thick. Its surface was thus 19 feet below low water. This rubble was all thrown in by hand, and no stone weighed more than from 1 cwt. to 1½ cwt. Although waves of 15 feet to 20 feet in height passed over it, it was never disturbed in the smallest degree. There was, however, no superstructure upon it other than one of comparatively open pile-work, which only broke, but did not reflect, the waves.

---

[1] The range of ordinary spring tides was 7 feet.

After the failure of the Madras breakwater, it was found, on examination, that portions of the rubble forming the base had been drawn out from beneath the blocks forming the vertical superstructure at a depth of 23½ feet, and that rubble stones weighing from 5 to 50 lbs. had been displaced at depths of at least 40 feet.[1]

The surface of a rubble mound surmounted by a superstructure should either be carried up well above high water, and be maintained at that level—as in the case of the Holyhead breakwater—so as to make the waves break and expend themselves upon it, or it should be kept at such a depth below low water as not to seriously affect the character of the waves, or be exposed to their disturbing action.

There can be little doubt that failure to recognize this, in the case of the Alderney breakwater, largely contributed to the destruction of that work.

If it should be intended to make a mound breakwater, with superstructure, answer the purpose of a quay, the rubble on the harbour side must either be kept well down, or jetties must be projected so as to give sufficient depth of water alongside of them to accommodate vessels of the class frequenting the port.

In determining the direction to be taken by a rubble mound breakwater, special attention should be paid to that of the waves during the heaviest gales, and the work should, if possible, be laid out so as to make the waves break square upon it. When waves break obliquely upon a rubble mound they cause the stone to travel, thereby necessitating an undue amount of maintenance.

Sometimes it has become necessary to construct groynes to check this travelling of the rubble; and in other cases, as has already been stated, the more expensive expedient of facing the mound with pitching above the low-water mark has been resorted to. At the outer end of the Holyhead breakwater, old heavy chains were deposited in coils, and shackled together so as to form mats over the surface of the rubble, and they were found to be very effective in checking its movement.

When mound breakwaters are projected from the shore, they are most expeditiously and economically constructed from a staging, such as was adopted at Holyhead and Portland.

[1] Report by Sir G. Molesworth, consulting engineer to the Government of India.

Where the mound is isolated, as at Plymouth and Cherbourg, it becomes necessary—unless the gap between the shore and the breakwater can be bridged by the staging—to convey and discharge the material by means of hopper-barges. I shall, however, have more to say on this subject later on.

In constructing the Plymouth breakwater, only rubble of large size was used in the mound, the smaller stone having been separated from it and cast aside. At Holyhead and Portland, large and small were used indiscriminately.

The question as to whether the rubble forming a mound should all be of large size, or whether it should be a mixture of different sizes, just as it comes from the quarry, is one upon which opinions differ.

The objections which have been advanced against the admixture of small material are chiefly based upon the idea that the smaller stones become rounded and form a carriage to facilitate the movement of the larger ones; and also that by their erosive action the larger blocks are worn away, as also the face of any superstructure that may be placed upon the mound.

No doubt small material in undue proportions is open to these objections, and is, further, likely to give rise to increased settlement. On the other hand, a moderate admixture of small material, by filling up all interstices, must conduce to the stability of a mound.

Sometimes the material is sorted, the smallest of it being placed in the centre and at the bottom of the mound, while the roughest is reserved for the sea-face and upper portion, where wave-action is most felt. This system was adopted in constructing some of the Mediterranean breakwaters. Mounds thus formed, not being homogeneous, are liable to settle unequally and cause trouble when superstructures are placed upon them.

Much of the trouble which was experienced at Plymouth, through the instability of the mound, was attributed to the fact of all the small stone having been excluded from it, whereby large interstices were left, into and through which the waves played.

In order to mitigate this evil as far as possible, the small material, which had been discarded, was afterwards spread over the mound, in the hope that it might, by the action of the waves, be carried in amongst the larger stones and bind them together.

It is, no doubt, well to select the largest of the stone for deposit on the weather slope and top of the mound; but if this should involve reserving stone to any great extent, either in the quarry or elsewhere, the cost of the work might be much increased, inasmuch as it would necessitate the handling of the material twice, or oftener, and would, further, be likely to cause inconvenience by congesting the quarry and works.

The quartzite stone of which the mound of Holyhead breakwater is composed weighs about 166 lbs. per cubic foot, or 13½ cubic feet to a ton. In the mound, one ton occupies somewhat less than 20 cubic feet. The voids are therefore about one-third of the whole mass of the mound.

Casual reference to the shortcomings of Alderney breakwater has already been made in this and in some of the preceding chapters, but before proceeding further it will be well to draw attention more directly to the several lessons which that great work teaches.

It may here be remarked that there is no branch of the engineering profession which is so dependent upon experience —especially that gained by failures—as the one which deals with the construction of sea-works. The practical knowledge which has been acquired during recent years in constructing breakwaters of various types, is therefore of the greatest value.

Fortunately, those in charge of works have, as a rule, been ready, not only to admit their failures, but also to give to the profession the benefit of the experience gained by them. In alluding to them so freely as I do, I therefore trust the reader will acquit me of any wish to disparage the works of others, and will recognize that my only object is to direct attention to the useful lessons which they teach.

It is not easy, in the present day, to realize the disadvantages under which the engineers of fifty or sixty years ago laboured, in having no works of magnitude, such as they have left us, to guide them in their designs. Even now, with all our experience, winter storms remind us very forcibly, almost every season, that we are still far from being infallible.

But to return to our subject. As the construction of Alderney breakwater progressed, the weak points in its design became manifest, and the section was altered from time to time as experience showed to be desirable. Sections of this breakwater, as constructed, will be found in Figs. 42 and 43–45.

The chief lessons to be learnt from this work—some of which have already been referred to—are:—

(*a*) The injurious effect upon the character of waves, which is produced by a mound foreshore, situated as that at Alderney is in regard to the levels of high and low water (see pp. 25–31). Referring to this subject, Sir John Coode remarked, "No doubt the breakwater at Alderney was exposed to a tremendous sea, but this was not wholly due to the exposure of the site. No one could deny that the exposure was great; *but the very heavy sea against the pier was mainly due to the peculiar configuration of the bank, and to the profile of the work itself.* A similar thing took place at the old Eddystone

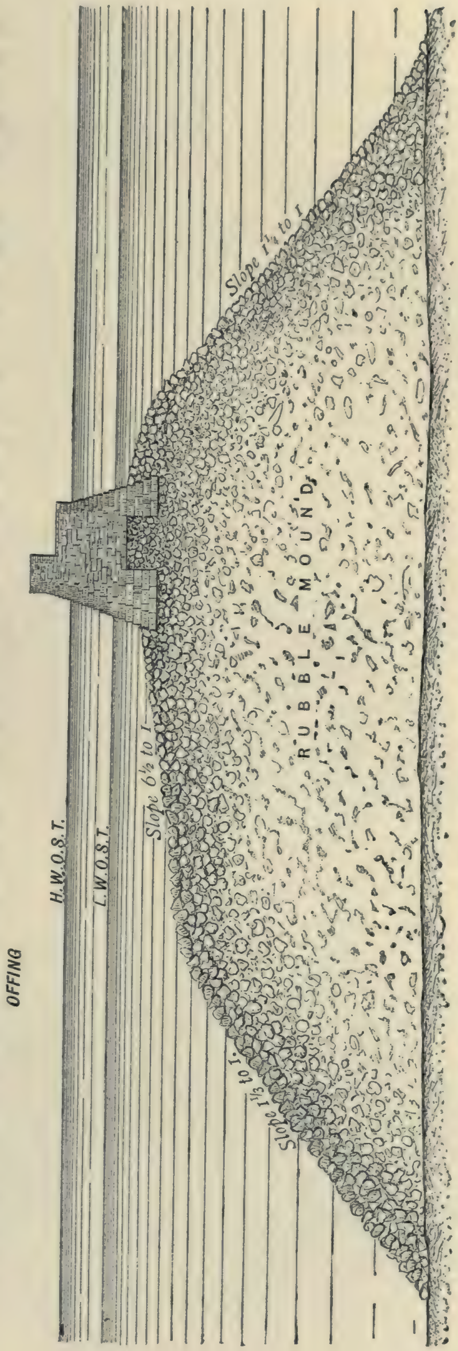


FIG. 42.—Alderney breakwater. Cross-section[1] (for enlarged sections of the superstructure, see Figs. 43-45).

---

[1] *Min. Proc. Inst. C.E.*, vol. xxxvii. pl. iii.

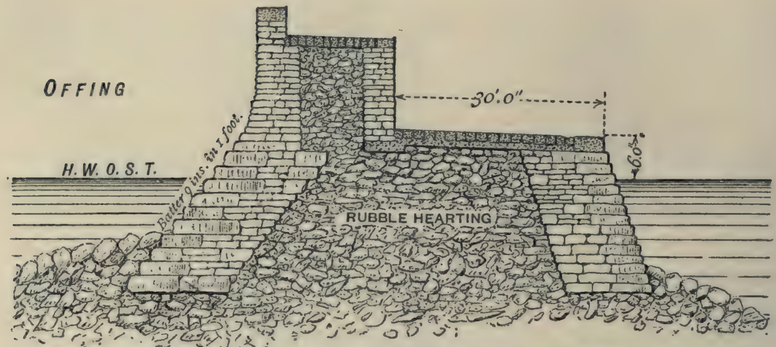


Fig. 43.—Alderney breakwater.[1] Cross-section of superstructure from the shore out to 410 feet.

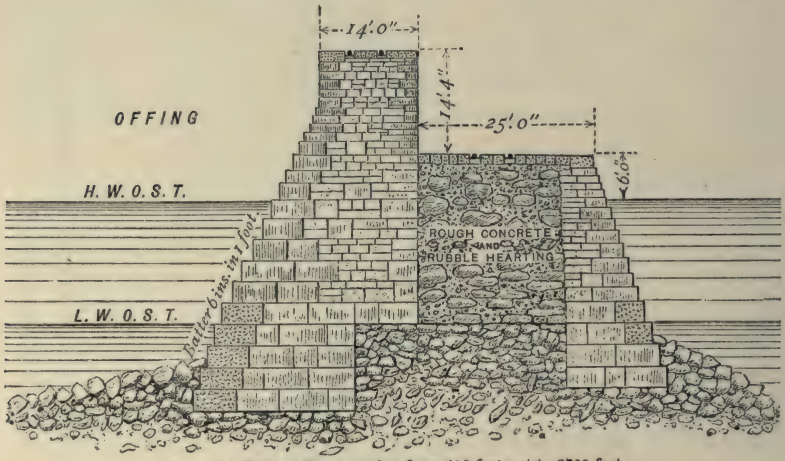


Fig. 44.—Ditto. Cross-section from 410 feet out to 2700 feet

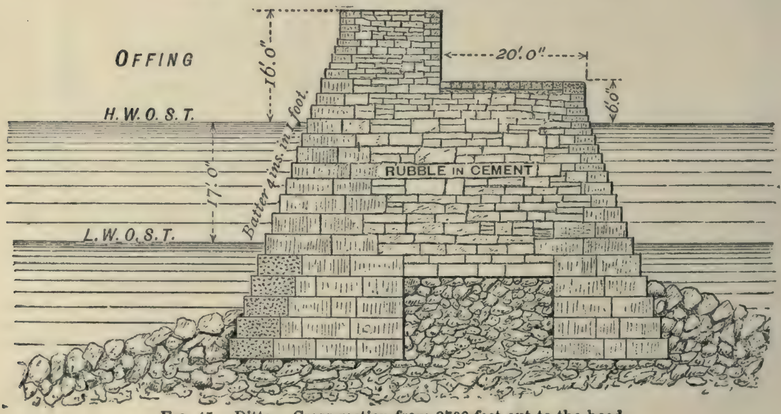


Fig 45.—Ditto. Cross-section from 2700 feet out to the head.

[1] *Min. Proc. Inst. C.E.*, vol. xxxvii. pl. iv.

lighthouse,[1] where, with a similar profile, at the close of a gale, the sea would often break over the top of the lantern."[2]

Sir John Hawkshaw, who, in company with Sir Andrew Clarke, C.B., R.E., was requested by the Board of trade to report upon this work, stated that—

> "From the shape of the mound and of the wall, the seas were thrown up to a considerable altitude; in falling back again their momentum drew away the deposit from the base of the wall, and the bottom courses dropped down, having nothing to stand upon. The sea then got to the rubble hearting between the two legs of the wall, fetched out that, and in a short time worked through the other portion of the wall on the harbour side, making breaches clean through."[3]

(*b*) The liability of a masonry superstructure to be dislocated by settlement, when placed upon a mound of such huge dimensions, and in such an exposed position as that at Alderney.

The settlement of the mound at Alderney equalled one-twentieth of its height, and amounted to fully 6 feet at the seaward end, where the depth at low water springs was about 133 feet.

This large settlement caused cracks and fissures to appear in the superstructure, the air and water within which, being compressed by the wave-stroke,[4] forced out the face stones, and resulted in serious damage.

(*c*) The danger of loose or weak hearting, as pointed out in Chap. V., pp. 80–82 (see Fig. 14, p. 80).

The waves made breaches right through the breakwater (Fig. 46.)

(*d*) The inexpediency of giving much batter to the sea face of a breakwater, inasmuch as it relieves the face stones of weight and facilitates their withdrawal.

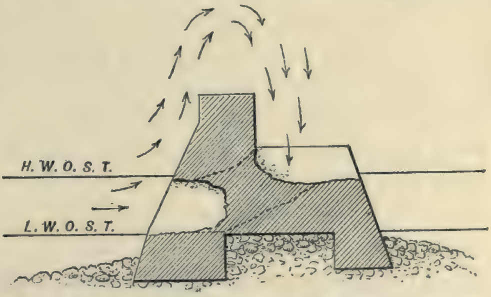


FIG. 46.—The unshaded portions show the damage in progress, the dotted lines representing the ultimate breach.

---

[1] The superiority of a vertical face over a curved sloping face, as regards the throwing up of water, was very clearly demonstrated during the building of the new Eddystone lighthouse—which has a vertical cylindrical base—while the old one, with its curved battered face, was yet standing.

[2] *Min. Proc. Inst. C.E.*, vol. xxxvii. p. 93.

[3] *Ibid.*, p. 95

[4] See pp. 107 *et seq.*

This was exemplified by the apparent ease with which face stones were withdrawn.

A batter of 9 inches in a foot was at first adopted; this was afterwards reduced to 6 inches, and later still to 4 inches; but even that was too great.

(*e*) The evil effect of parapets in increasing the recoil of waves and the height to which water is thrown; also in unequally loading the foundation, whereby irregular settlement and longitudinal cracks are likely to be brought about.

The high parapet at Alderney caused the whole force of the waves to be thrown against the superstructure, and immense volumes of water were projected, during storms, to a height of fully 200 feet, by the falling of which the roadway of the breakwater was frequently damaged, and the rubble mound scooped out.

Sir John Hawkshaw and Sir Andrĕw Clarke recommended, as a remedial measure, the entire removal of the parapet—or promenade wall, as it was called—and the formation of a wave-breaker, composed of heavy concrete blocks deposited along the seaward face of the breakwater, and extending to slightly above high-water mark. As an alternative, it was suggested that the rubble mound might be raised up to or above the level of high water, as at Holyhead; but the amount of rubble necessary for this purpose, in view of the exposure of the site and the great depth of water, would have been very large.

B.—*Mound Breakwaters of Concrete Blocks, thrown together pell-mell.*

Breakwaters constructed entirely of pell-mell block-work are few in number, the reason, no doubt, being that a saving in cost may be effected by a judicious use of rubble in combination with the blocks.

Such combinations are almost endless, but the following may be cited as examples:—

(*a*) A rubble base, brought up to within, say, 15 or 20 feet of low water, with a pell-mell mound of blocks placed upon it. This system was adopted for the main portion of the breakwater at Algiers, for the outer portion of the breakwater at Port Said, and for the breakwater at Port Erin,[1] Isle of Man. A breakwater of this type is shown in Fig. 47.

---

[1] In the Port Erin breakwater, the surface of the rubble mound was only from 2 to 5 feet below low water of spring tides.

(*b*) A mound of sorted rubble, of which the smaller sizes are used to form the core, the larger being reserved for the outer coating. This mound is capped by one of pell-mell blocks, a layer or covering of which is also carried down to the sea-bed on the weather side, so as to entirely protect the seaward slope. The outer portion of the breakwater at Algiers was constructed in this manner. A typical section is given in Fig. 48.

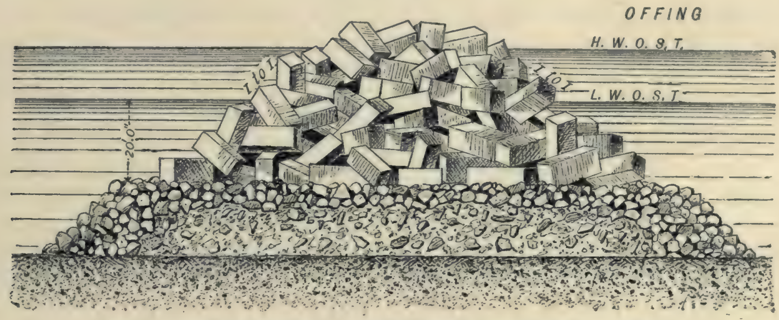


Fig. 47.—Mound breakwater. Pell-mell blocks on rubble base. Type (*a*).

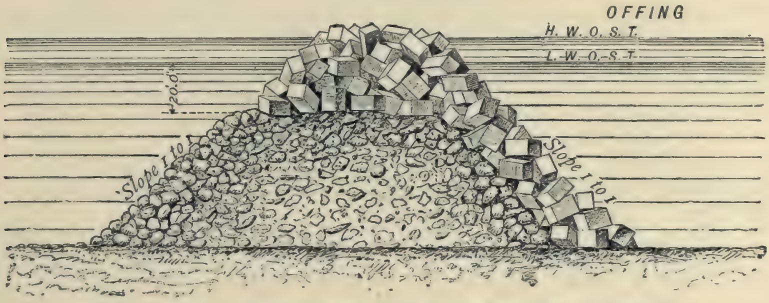


Fig. 48.—Ditto. Rubble, faced and capped with concrete blocks. Type (*b*).

(*c*) A mound of pell-mell blocks, backed up on the harbour side by rubble, in order to prevent the passage of undulations and silt, as was done at Alexandria (Fig. 49, p. 210).

(*d*) A pell-mell block mound with a concrete or masonry superstructure erected thereon, as at Leghorn and St. Jean de Luz (Fig. 50, p. 210).

(*e*) A rubble mound with superstructure; the seaward slope

TORONTO

being faced with pell-mell blocks, as at Marseilles and Boulogne (Fig. 51).

(*f*) A low rubble mound with vertical superstructure, having a wave-breaker of pell-mell blocks on the weather side, as at Madras and Mormugão (Fig. 39, p. 195).

The slopes assumed by rubble in breakwaters of the mound type are, *cœteris paribus*, proportionate to the size and specific gravity of the stones of which the mound is composed or faced. The same may be said of mounds formed of concrete blocks.

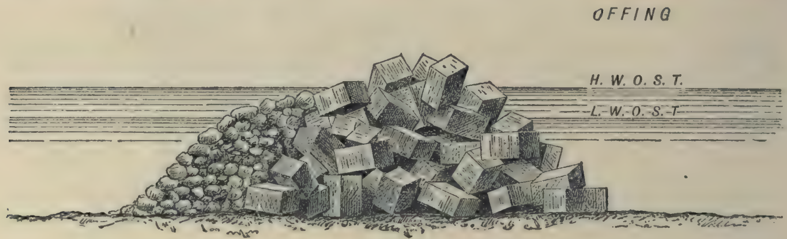


Fig. 49.—Mound breakwater. Pell-mell blocks backed with rubble. Type (*c*).

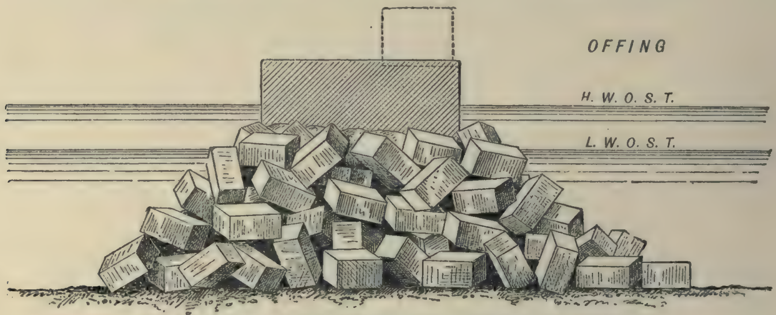


Fig. 50.—Ditto. Pell-mell blocks with superstructure. Type (*d*).

Inasmuch, however, as concrete is a costly material, it should be used as sparingly as possible, having due regard to the stability of the work.

In all cases, therefore, where pell-mell block mounds are used, the slope of the mound should be steep, and the blocks proportionately large.

Large blocks are as easily made as smaller ones, and the only addition to their cost is due to the heavier, and therefore more expensive, plant that is required for handling them; but even this, in the case of large works, would probably be more than compensated in other ways.

A block-mound with steep slopes, in addition to the economy which it effects as regards quantity of material, possesses the further advantage of not intensifying the power of the waves in the manner that long rubble foreshores have been shown to do; it also occupies less ground than a rubble mound, which, in some situations, would be a great desideratum.

The voids in a pell-mell block mound, and the ruggedness of its slope, materially assist in breaking up waves and checking their run.

Although there is a large saving in the quantity of material required to form a concrete block mound, as compared with one of rubble stone, the cost per cubic yard of the former will probably be at least five or six times as much as of the latter, so there is not a great deal to be said in favour of block mounds from a pecuniary point of view.

The pell-mell system of constructing breakwaters has been more largely used in the Mediterranean than elsewhere, and it has, for the most part, proved satisfactory.

In some positions, however, as for instance at Biarritz, on the west coast of France, facing the Bay of Biscay, at Oran, and also at Port Erin, in the Isle of Man, breakwaters of this construction have suffered severely.

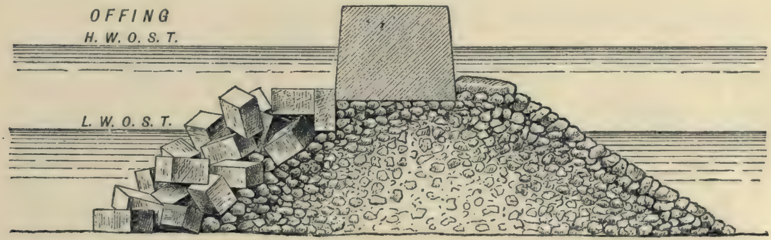


FIG. 51.—Section of breakwater with vertical superstructure on rubble base faced with pell-mell blocks. Type (*e*).

When a good class of rubble is available, a large saving may be effected by using it in combination with blocks in one or other of the modes already described; type (*e*), Fig. 51, forming a good example of this class of structure for sites where the exposure is not very great.

In constructing breakwaters of this type two points require special attention, viz.—

(1) To be careful not to expose more rubble at a time than is

necessary, having in view the danger of its being dispersed before it could be protected by blocks; and (2) not to use rubble of so small a size, on the seaward face, as to admit of its being drawn out between the blocks by the action of the waves.

In very exposed situations, it is obvious that in breakwaters of the (*e*) type, considerable risk would be incurred, during construction, by carrying up the rubble into the sphere of wave-action.

Mixed rubble may be safely used in the lower section of the mound; and by carrying this well forward as the work advances, the larger class of rubble may be selected and used as a coating, without entailing inconvenience or additional cost.

A mound breakwater with a rubble core checks the passage of sand, mud, and undulations into a harbour much more effectually than a mere mound of blocks can do.

When a pell-mell mound is placed upon a rubble base, the latter should be of sufficient width at the top to allow of a level benching extending beyond the toe of the block slope. This may vary in width from 10 to 20 feet, or more, according to circumstances, and should always be composed of, or be protected by, rubble of large size.

In a pell-mell mound formed entirely of concrete blocks, only about $\frac{2}{3}$ or $\frac{3}{4}$ of its cube will be solid, the remaining $\frac{1}{3}$ or $\frac{1}{4}$ being represented by voids between the blocks.

The size of blocks for pell-mell work suited to any particular site can only be decided by analogy, and by a careful study of all the conditions affecting such site. The facts in the following table, pp. 214, 215, relating to a few existing works, may therefore be of use in considering this point.

During recent years, experience has shown that blocks—weight and other conditions being equal—laid in stepped courses are more stable than when deposited pell-mell.

In some of the more recent works, especially those carried out by Italian engineers in the Mediterranean, stepped block facing has therefore been adopted in preference to pell-mell work. The new breakwater at Cette, in the south of France, has also been constructed in this way.

A type section illustrating this mode of construction is given in Fig. 52, p. 213.

The placing of blocks in stepped courses is naturally somewhat more expensive than merely throwing them into the sea pell-mell; and the system is open to the objection, already pointed out, that the lower blocks derive but little help from the weight of those above them. When, however, very heavy blocks are employed, this objection in a measure disappears.

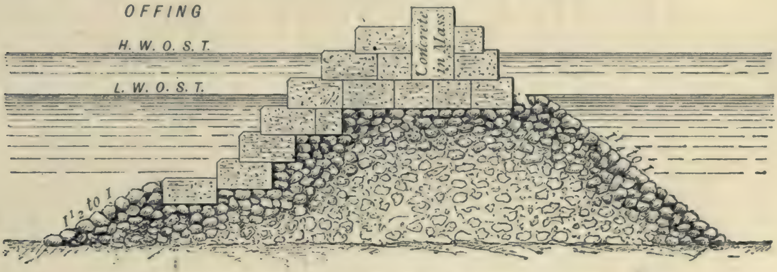


FIG. 52.—Mound breakwater faced and capped with stepped block-work. Type (*g*).

Notching the blocks in the manner shown in the above sketch (Fig. 52), or slightly inclining them backwards (Fig. 53), as was done in the breakwater at Cagliari, in Italy, increases their stability, while adding but little, if anything, to their cost.

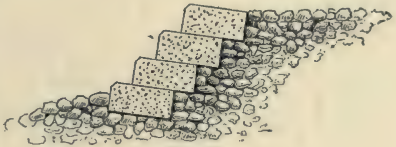


FIG. 53.

Breakwaters constructed on this principle in the Mediterranean, in positions where they are sometimes subjected to the impact of waves as high as 21 feet, appear, so far, to have stood well, they having cost but little in maintenance.

They are easily constructed by means of pontoons fitted with derricks, the speed with which the work is carried on being thus largely a question of the amount of plant employed.

Breakwaters of this type are comparatively free from sea-risk whilst in progress.

All the blocks are bedded " dry," no mortar being used.

The weight of the blocks employed by the Italian engineers in constructing the breakwaters to which I have referred, varied from about 28 tons to 36 tons each.

Name of port.	Type of breakwater.	Illustrated in Fig.	Longest fetch in miles.	Depth at L.W.O.S.T., or at ordinary sea-level for Mediterranean ports.	Range of spring tides.	Inclination of seaward slope.	Weight of blocks.	Remarks.
				feet.	feet.		tons.	
Port Said (outer portion).	(*a*) Pell-mell blocks on rubble base.	47 p. 209.	400	25 to 30	—	1 to 1	20	The direction of longest fetch is about north-west, or nearly square to the line of breakwater. In the main portion of the breakwater there is no rubble mound, the breakwater being composed entirely of concrete blocks. The blocks are quite stable.
Port Erin (Isle of Man).	(*a*) Pell-mell blocks on rubble base.	47 p. 209.	60 to 70 In westerly direction (square to breakwater).	36 Top of rubble mound being only from 2 feet to 5 feet below L.W.O.S.T.	18	1 to 1	10 to 15	Although the site is apparently sheltered in a south-westerly direction by the Calf of Man, south-westerly gales veering to north-west cause the heavy waves which roll in from the Atlantic to wheel round this point. The blocks stood undisturbed for thirteen years, after which the breakwater was practically destroyed by an exceptionally heavy gale.
Algiers (outer portion).	(*b*) Rubble mound, faced and capped with pell-mell concrete blocks.	48 p. 209.	550	36 to 108	—	1 to 1 In some places $1\frac{1}{4}$ to 1	33	The direction of longest fetch is about north-east, or nearly square to the line of the breakwater. The block capping is surmounted by masses of concrete, weighing about 220 tons each, which were made *in situ*. The blocks are quite stable. It was ascertained, during the construction of this work, that blocks weighing 20 tons were liable to be moved by the waves. Blocks of stone weighing from 5 to 10 tons each were unstable, even at a slope of 6 to 1.

Alexandria.	(*c*) Pell-mell blocks, backed with rubble.	49 p. 210.	980	24	—	1 to 1	20 to 25	These blocks are quite stable.
Biarritz.	Pell-mell blocks from sea-bed up to 7 feet above H.W., with rubble stone in the interstices.	—	Open to the Atlantic (Bay of Biscay).	23	12	1 to 1	33	This breakwater sustained serious damage, the blocks, notwithstanding that they rested upon a rock bottom, being unstable.
St. Jean de Luz (Artha breakwater).	(*d*) Pell-mell blocks from sea-bed up to a little above low water of spring tides, surmounted by concrete superstructure; small quantity of rubble stone in interstices.	50 p. 210.	Open to the Atlantic (Bay of Biscay).	35	12	1 to 1	44	Highest waves measure about 23 feet, trough to crest. The blocks in this structure are not stable.
Ymuiden (Holland).	Vertical wall on rubble base, with wave-breaker on seaward side.	—	Practically unlimited. Open through North Sea to the Arctic Ocean.	26	5½	1½ to 1	5 to 10 with capping of 20-ton blocks.	Blocks in wave-breaker were disturbed and pulled down until they took a slope of 1½ to 1, at which angle there has been very little movement.
Mormugão.	Ditto.	39 p. 195.	1500	28	6	1¼ to 1	20	Notwithstanding the long fetch, waves never attain a greater height than 15 feet. Blocks in wave-breaker were disturbed a little at first by settlement of rubble-mound, but were subsequently quite stable.
Marseilles (La Joliette).	(*e*) Vertical superstructure on rubble base faced with pell-mell blocks.	51 p. 211.	120	30 to 60	—	1 to 1 below water; 2½ to 1 above water.	25½	The waves drew down the blocks and formed the slopes to the inclinations named, at which they remain stable during the heaviest gales.

PARTICULARS RELATING TO SITES, CONSTRUCTION, COST, MAINTENANCE, ETC., OF SOME EXISTING BREAKWATERS.

Name of breakwater or where situated.	Type of breakwater.	Length of greatest fetch.	Depth of sea-bed below low water spring tides.	Nature of sea-bed.	Range of ordinary spring tide.	Average cost per lineal foot of breakwater.	Average rate of progress per annum.	Total length of breakwater.	Average annual cost of maintenance per lineal foot.	Remarks.
		miles.	feet.		feet.	£	feet.	feet.	s. d.	
Holyhead.	Rubble mound with vertical superstructure (see Fig. 41, p. 199).	100	Average 38 greatest 55	Boulder-clay.	17	163 of which the superstructure cost £36.	297	7860	1 : 3	Constructed from timber staging. All free labour.
Portland.	1700 feet; rubble mound with vertical superstructure. 6400 feet; rubble mound without superstructure.	150	Average 44 greatest 58	Clay or stiff mud.	6¾	127	405	8100	9 : 9 (Average during the five years 1889–1893, exclusive of superintendence and plant.)	Constructed from timber staging. Stone quarried and loaded into waggons by convict labour.
Genoa[1] (New Mole),	Rubble mound with vertical superstructure.	572	26 to 46	Compact sand.	—	No data.	530	3180	6 : 9	Highest waves measure 21 feet from trough to crest.
Alderney.	Rubble mound with vertical superstructure.	Open to the Atlantic Ocean.	Average 60 greatest 133	Rock and compact sand.	17	235	275	4700	Very variable. During the 8 years 1864–1872 the average cost of maintenance was £2 5*s.* 3*d.* per lineal foot.	In the year 1862 the superstructure was advanced 562 lineal feet. The breakwater was completed in 1864. In 1873 the outer length of about 1800 feet was abandoned, the re-

										maining length being maintained for several years at an average cost of about 24s. per lineal foot.
Cherbourg.	Ditto.	100	Average 39 greatest 43	Sand and shells.	19	168	170	11,880	No data.	This work was in course of construction for about 70 years, during which period operations were sometimes either wholly or partially suspended for several consecutive years.
Plymouth.	Rubble mound, slopes faced with stone pitching.	Open to the Atlantic Ocean.	30 to 42	Clay.	15½	About 300	264	5280	9 : 0 (Average during the five years 1889–1893, exclusive of superintendence and plant.)	This breakwater has required such extensive repairs that the date of its completion can scarcely be stated. It was, however, commenced in the year 1812, and may be said to have occupied about 20 years in construction.
Kingstown.	Ditto.	75	Average 20 greatest 27	Sand and rock.	11¼	74	498 or 249 feet for each pier.	9440 total length of the two piers.	2 : 0	

---

[1] Luiggi on "Breakwaters and Sea Defences in Italy," "Minutes of Proceedings," International Maritime Congress, 1893.

Name of breakwater or where situated.	Type of breakwater.	Length of greatest fetch.	Depth of sea-bed below low water spring tides.	Nature of sea-bed.	Range of ordinary spring tide.	Average cost per lineal foot of breakwater.	Average rate of progress per annum.	Total length of breakwater.	Average annual cost of maintenance per lineal foot.	Remarks.
		miles.	feet.		feet.	£	feet.	feet.	s. d.	
Catania [1] (New Mole).	Rubble mound, faced on seaward side with pell-mell concrete blocks to the level of 23 feet below the water-line, and capped above water with concrete blocks laid in stepped horizontal courses.	746	33 to 46	Sand and mud.	—	72	274	4383	5 : 6	Highest waves measure 16 feet from trough to crest.
Alexandria.	Mound of pell-mell concrete blocks, backed with rubble (Fig. 49, p. 210).	980	6 to 24	Sand.	—	200	4837	9675	No data.	Constructed by means of barges, the upper blocks being placed by floating steam shears.
Leghorn [1] (Curvilinear Mole).	Mound of pell-mell concrete blocks with vertical superstructure.	65	33 to 39	Rock with overlying sand.	—	131	333	3668	8 : 2	Highest waves measure 15 feet from trough to crest.
Naples [1] (S. Vincenzo Mole).	Rubble mound, faced on seaward side with concrete blocks to the level of 23 feet below the water-line, and capped with simi-	345	82 to 105	Compact sand.	—	186	125	623	13 : 3[2]	Highest waves measure 16 feet from trough to crest.

	lar blocks above water, all laid in stepped horizontal courses.									
Barletta[1] (Eastern Mole).	Rubble mound, faced throughout on seaward side with concrete blocks laid horizontal and stepped. Top of breakwater 11 feet 6 inches above water-line.	109	16 to 30	Compact sand.	—	27	510	4593	No data.	Highest waves measure 15 feet from trough to crest.
Admiralty Pier, Dover.	Vertical, concrete blocks faced with granite.	150	Average 25 greatest 45	Chalk rock.	19	345	88	2100	In the year 1877 the parapet wall of this pier, for a length of about 1050 ft., was carried away. With this exception the pier has required very little expenditure on maintenance.	
Aberdeen South Breakwater.	Concrete blocks laid in horizontal courses, surmounted by mass concrete.	400	Average 15 greatest 22	Rock, clay, boulders, and gravel.	12½	65	262	1050	14 : 0	

---

[1] Luiggi on "Breakwaters and Sea Defences in Italy," "Minutes of Proceedings," International Maritime Congress, 1893.

[2] Includes some expenditure on new work.

Name of breakwater or where situated.	Type of breakwater.	Length of greatest fetch.	Depth of sea-bed below low water spring tides.	Nature of sea-bed.	Range of ordinary spring tide.	Average cost per lineal foot of breakwater.	Average rate of progress per annum.	Total length of breakwater.	Average annual cost of maintenance per lineal foot.	Remarks.
		miles.	feet.		feet.	£	feet.	feet.	*s.* *d.*	
Fraserburgh.	Mass concrete superstructure on base of bag-work.	Open to the Arctic Ocean.	Average 10 greatest 25	Rock, boulders, and sand	12	52	215	860	18 : 3	Water deepens somewhat abruptly near seaward end.
Newhaven, Sussex.	Ditto.	Open to the Atlantic Ocean.	Average 12 greatest 18	Sand and clay.	20	70	296	2700	*Nil.*	
Manora (Kurrachee).	Sloping blocks on rubble base.	500 Waves never exceed 15 feet in height.	Average 23¾ greatest 30	Sand.	7¼	72	376	1503	7 : 3	This breakwater is, for the greater part of its length, only carried up to the level of 3 feet 6 inches below high water. When block-setting was in full swing, the average advance per annum was about 500 feet. In one season it amounted to 710 feet.
Colombo.	Ditto.	Open to the Indian Ocean, but waves do not exceed 15 feet in height.	Average 24 greatest 41½	Rock and sand.	2	140	383	4212	No data.	In this work convict labour was largely employed. The time occupied in constructing the breakwater, including preliminary

										work, was about eleven years. The average rate of progress per annum was therefore 383 feet; but during the seasons when block-setting at the breakwater was in progress the average advance per annum was 592 feet. This did not, however, include the capping of mass concrete, which was not put on till afterwards.
Mormugão.	Sloping blocks on rubble base, with wave-breaker.	Open to the Arabian Sea, say 1500 miles; but waves do not exceed 15 feet in height.	Average 28 greatest 29 almost level throughout.	Mud, merging into stiff clay.	6	64	370	1800	Almost *nil.*	When block-setting was in full swing, the rate of advance averaged about 109 feet per *month.*

CHAPTER XII.

PIER-HEADS.

Necessity for strengthening the ends of piers—Range along harbour side of piers—Various types of pier-heads—Pier-head lights and fittings.

THE end of a pier, whether during construction or after the work has been completed, is, *cæteris paribus*, the most vulnerable part of the structure, because it lacks the support which other portions of the work mutually afford each other. It is, moreover, usually placed in deeper water, and subjected to rougher usage, both from waves and from shipping, than any other part of the work. It is, therefore, proper that additional strength should be given to it. This may be done in a variety of ways, according to circumstances.

If it should be intended to use a pier as a quay for the berthing of vessels, it is desirable that waves, as they pass the pier-head, should be prevented from running along the harbour side of the pier and creating an inconvenient range there. With this object in view, the head may be made to take the form of a right-angled kant or spur, as illustrated by the following sketch (Type A, Fig. 54).

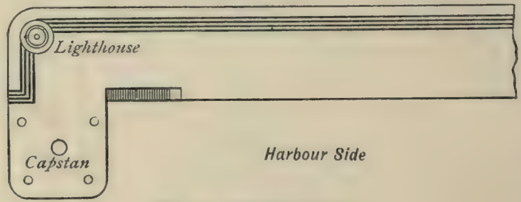


FIG. 54.—Pier-head, Type A.

In cases where range along the harbour side of a pier is unobjectionable, a head of circular form is commonly adopted (Type B, Fig. 55). A round head is less liable to inflict damage upon vessels coming into collision with it, or to sustain damage itself by vessels striking it, than one of more rectangular form.

Fig. 56, Type C, represents a head of hooked form, in which the advantages of a circular head and of a spur are combined.

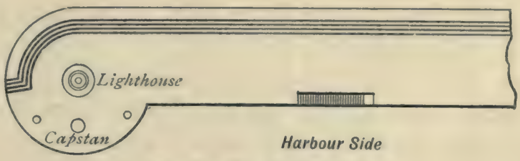


FIG. 55.—Pier-head, Type B.

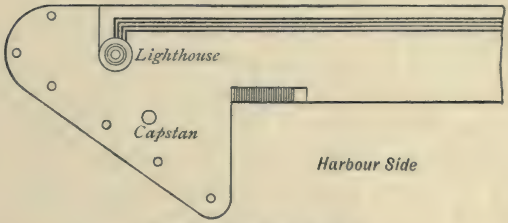


FIG. 56.—Pier-head, Type C.

The superstructure of the Holyhead breakwater terminates with a hammer-shaped head (Type D, Fig. 57), which is founded at the level of 20 feet below low water. This somewhat exceptional form was adopted in order to prevent small rubble from the mound travelling around the end of the breakwater, and also to give protection to the end of the mound itself; it furthermore, in a measure, shelters the landing-steps on the harbour side of the pier from waves wheeling round the end.

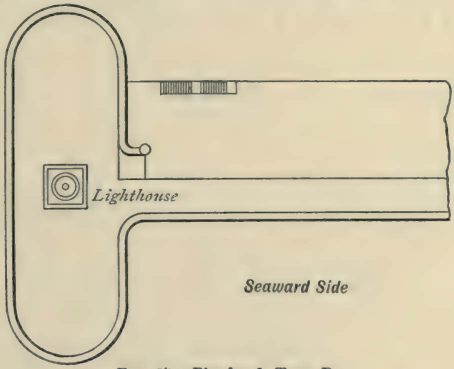


FIG. 57.—Pier-head, Type D.

Sometimes—especially in small fishery harbours—piers are made to terminate with a semicircular or square end only the width of the pier, additional strength being given either by adopting a better class of masonry, by dovetailing or dowelling the blocks together, or in some other way. Piers terminating in this manner are in some ways more convenient than those with hooks or projections, inasmuch as they afford greater facilities for small vessels or fishing-boats working along them, and so getting away to sea. In some situations, however, this convenience may be more than counterbalanced by the run of waves along the pier, which often proves very troublesome.

This wheeling of waves around pier-heads, and the range which it causes along the harbour side of piers, is not, as a rule, sufficiently realized in designing works, and it not infrequently happens that it has to be dealt with later on.

Lights, for the guidance of vessels entering harbours at night, are usually exhibited from pier-heads. This necessitates the erection of small lighthouses, for which room should be provided when designing the heads. Dioptric lights of the fourth or fifth order are suitable for this purpose; but for small fishery harbours sixth-order lights will generally be found sufficient.

A pier-head is also usually furnished with a capstan—for the arms of which a clear sweep of from 12 to 15 feet radius is required—and with mooring-posts, fairleads, etc.

CHAPTER XIII.

WAVE-SCREENS AND FLOATING BREAKWATERS.

Designs for wave-screens and floating breakwaters based upon wrong hypotheses—Description of wave-screens proposed by Hays, Scott, and Calver—Floating breakwaters—Examples of, in nature—Icebergs—Weed-fields—Size of effective floating breakwater—Behaviour of vessels riding at anchor—Impossibility of mooring floating breakwaters—Inefficiency of floating breakwaters—Booms at harbour mouths—Floating-weed type of breakwater—The mooring of lightships.

VARIOUS proposals have from time to time been made for intercepting and breaking up waves by means of screens and floating breakwaters. In such designs the prominent idea seems to have been that waves could be stopped or broken up and destroyed without the structures by which this was brought about having to sustain the shock of the wave-impact; in other words, that action and reaction are not equal.

There can, however, be little doubt that the strain upon any structure employed in the reduction of waves, by whatever means it may be brought about, will be in exact proportion to the amount of reduction effected in a given time.

In the year 1858,[1] Mr. W. B. Hays gave evidence before a Select Committee on Harbours of Refuge, respecting a wave-screen which he had designed, and which he claimed was adapted for harbours of refuge in deep water. Fig. 58, p. 226, which is copied from a drawing illustrating the committee's report,[2] represents the structure referred to, as adapted to a depth of 36 feet at low water, and a tidal range of 10 feet.

The advantages of this system were stated to be (*a*) its small cost; (*b*) the facility and rapidity with which it could be erected; and (*c*) that, in consequence of the inconsiderable depth of the actual breakwater below the surface, the flow of the tide would be uninterrupted, and all risk of silting within the harbour be avoided.

---

[1] A description of Mr. Hays's system was also published, in pamphlet form, in the year 1856, reprinted from the *Civil Engineers' and Architects' Journal.*

[2] "Report of Select Committee on Harbours of Refuge, 1858."

The screen was described as consisting of a number of parallel plates of iron, inclined towards the sea at an angle of about 55 or 60 degrees with the horizon, these being framed together in lengths of 30, 40, or 50 feet, and supported by piers formed of wrought-iron screw-piles, strongly braced together. The plates were to be placed at such an angle that the waves would be reflected from one to the other until all their energy was exhausted. The water would also (so it was claimed), through being thus reflected from plate to plate, tend to push the several

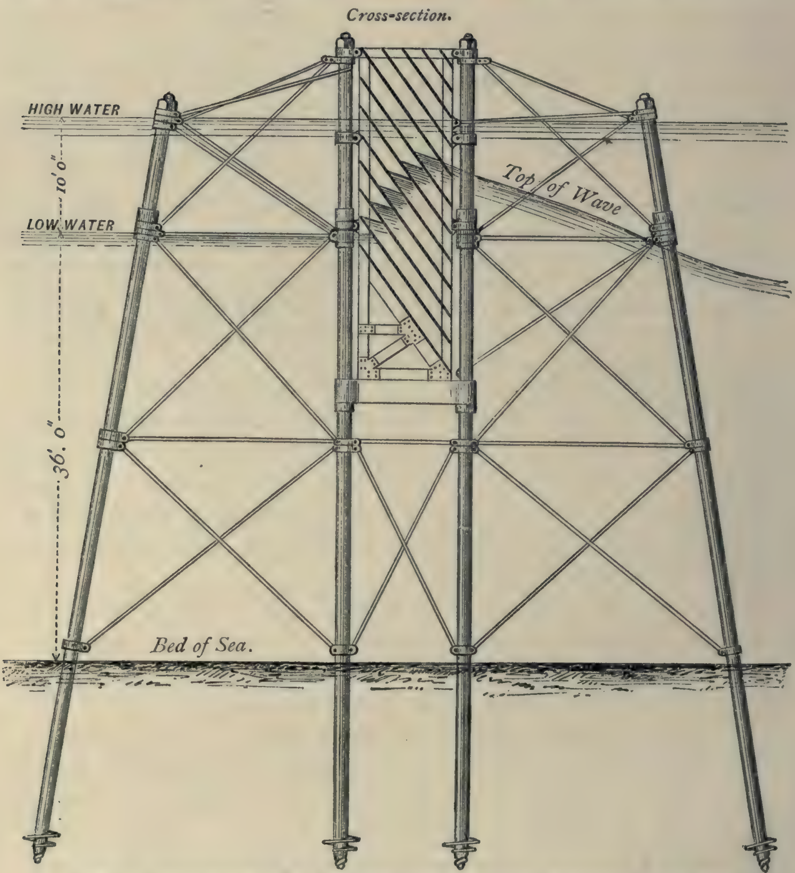


Fig. 58.—Wrought-iron louvered breakwater or wave screen, as proposed by Mr. Hays.

plates backward and forward at the same moment, the effect of such action being to almost neutralize the force of the waves upon these plates, freeing the structure in a great measure from the violent action of the sea tending to destroy it.

A small structure of this kind was, I believe, erected at the head of a jetty at Glenelg, near Adelaide (Australia), in the year 1858. Its form on plan was that of a crescent, facing in the direction of the prevailing winds, and its length was about 240 feet. The depth of water at low water springs was 11½ feet, the tidal range being 6 feet.

In a position sheltered by nature to the extent that Adelaide is, a structure of this kind might give some protection by combing down small waves; but in a short time, especially in a warm climate, the immersed louver-plates would, unless frequently scraped, become thickly coated, or even caked into a solid mass, by marine growth.

The removal of this from time to time would entail considerable cost, and would, further, be injurious to the plates; but if not done, the water would be unable to pass between them, and the screen would practically become a close breakwater, any real or assumed advantages of the louver-plate system being thus altogether nullified.

The idea of only carrying the louver-plates down to about 12 feet below low water probably originated in the old-fashioned and long-ago-exploded notion that wave-action did not extend below such level—at all events, to any appreciable extent. Later research and experience have, however, demonstrated the fallacy of such an idea, as has been pointed out in previous chapters.

A structure such as the one just described could only intercept small surface waves, and would, without doubt, be quickly destroyed in a heavy sea. Indeed, this view seems to be borne out by Mr. Hays's own statement. In the pamphlet before referred to I find him saying (p. 5)—

> "It should, however, be borne in mind that this breakwater is adapted only to situations where there is some depth of water; it is not calculated to resist the shock of breaking waves near a beach or in very shallow water."

It would thus appear that the ideas of the inventor respecting waves were not in accordance with more recent experience.

Another kind of wave-screen, somewhat resembling a huge gridiron, was proposed by Mr. M. Scott.

In this a rubble mound, rising to within about 15 feet of low water, similar to that adopted in ordinary mound breakwaters, was to have formed the base; and upon it it was proposed to build a face wall, up to or slightly above the level of low water, having counter-forts of masonry, about 20 feet apart, extending back upon the mound for a length of from 80 to 120 feet. The upper surface of these counter-forts was to have had a slope of 2 or 2½ to 1 from their junction with the face wall, and it was intended they should rise to a height of 50 feet above low water.

Upon their sloping faces, and spanning the distance between them, iron girders were to have been fixed, with spaces of about 18 inches between their flanges, thus forming a screen or grating.

It was claimed, in support of this form of screen, that as waves ran up it the water would drop through the spaces between the girders, and that a similar action would go on as the wave receded, if any of it should remain. This falling water, it was believed, would destroy any undulations which might be passing through the lower parts of the screen. It is not, however, quite clear that the waves would run up the grating in the manner contemplated. It seems more probable that they would be tripped up by the low face wall, and fall with great force upon the girders, which, in view of the power of such breaking waves, would require to be made exceptionally strong to withstand such repeated shocks.

In considering this design, it would appear that, in order to give the counter-forts sufficient stability, it would be necessary to employ quite as much material as would be required to construct a substantial solid masonry superstructure. The necessity for, or advantage of, the girderwork grating is not, therefore, very apparent.

Another form of wave-screen, as proposed by Mr. E. K. Calver, R.N., is shown in Fig. 59.

For a screen suited to a depth of 36 feet at low water, a tidal range of 15 feet, and a wave 15 feet in height, it was proposed that the piles should be 20 inches diameter, and be made of wrought-iron plates at least one inch in thickness. These were to be screwed into the bed of the sea for a depth of 10 feet, and where, from the nature of the bed, this was not practicable, some other means of fixing them was to be resorted to. Spaces were to be left between the piles equal to their diameter.

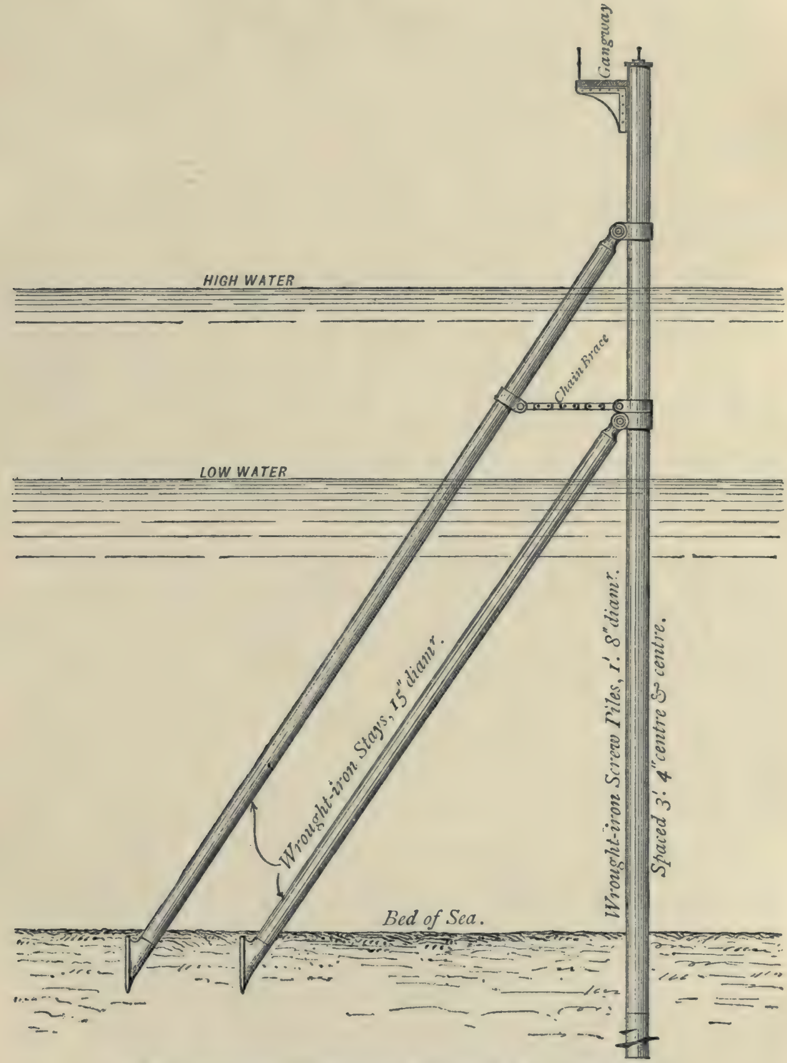

Gangway
HIGH WATER
Chain Brace
LOW WATER
Wrought-iron Stays, 15" diamr.
Wrought-iron Screw Piles, 1'. 8" diamr.
Spaced 3'. 4" centre & centre.
Bed of Sea.

FIG. 59.—Wave-screen as proposed by Mr. Calver, R.N. Cross-section.

The stays were to be 15 inches in diameter, and were to be fixed as shown in the drawing.

It was assumed that the foot of each stay would be buried beneath the surface by the action of the tidal current (where such happened to exist), while the ties would be fitted with movable collars to secure the various sections of the screen in their places, and to provide against irregularities of distance.

It was stated that the material used in the construction of such screens might be varied according to circumstances, piles of timber or cast iron being substituted for those of wrought iron where thought to be desirable.

The cost of a wave-screen such as this was estimated at £850,000 per sea mile, the value of the ironwork, delivered on the works, being taken as £20 per ton.[1]

It seems evident that the stays, to be of service, would have to be fixed in some more secure manner than that indicated in the drawing, seeing that the rush of water towards the breast of each wave, as it advanced (see Fig. 6, p. 25) would tend to push the screen forward, while the impact of the waves would drive it back. The stays would thus be alternately in tension and compression, and the screen would be pushed backward and forward by turns, in a manner that would be very trying to it.

During erection, a structure of this kind would be subject to great sea risk; and in view of the difficulties inseparable from such a class of work, and the small percentage of days upon which it could be carried on in exposed situations, its progress would be very slow.[2]

It would thus appear that the stability of such a structure would be small; that a considerable amount of undulation would be admitted into the harbour between the piles; that its erection would be slow and attended with considerable sea risk if in an exposed position; and that its cost, as estimated, would be more than sufficient to construct a substantial breakwater of one of the more ordinary types. Altogether, therefore, the design does not seem to have very much to commend it.

The more one considers wave-screens of the several types we have been describing, whether from a theoretical or practical point of view, the less desirable they seem to be; indeed, from experience in constructing iron piers and other sea-works, I feel satisfied that any attempt to arrest heavy seas by mechanical means must ultimately fail.

---

[1] "Report of Royal Commission on Harbours of Refuge, 1859," vol. i. p. 31. Also pamphlet "On the Construction and Principle of a Wave Screen," by E. K. Calver, R.N. (1858).

[2] It was proposed to screw these piles from a barge.

Apart from the force of the wind and waves, the probability of floating wreckage or of unmanageable vessels drifting down upon a wave-screen during a gale should not be lost sight of. This risk equally applies to floating breakwaters (so called) which we will now pass on to consider.

Floating Breakwaters.—If we look to nature for types of breakwaters, we find the mound type exemplified by boulder beaches, the vertical type by sea cliffs, wave-breakers or pell-mell work by huge boulders at the bases of cliffs, and floating breakwaters by gigantic icebergs and large areas of floating seaweed.

Engineers have been able, with more or less success, to copy the examples which nature thus presents, with the exception of the two last-named.

Icebergs and weed-fields, whenever they possess the attributes of breakwaters, are found to be of such gigantic proportions as to render imitation on a sufficiently large scale hopeless. Icebergs are, moreover, wanderers; and he would be a bold man indeed who would attempt to moor one.

A large iceberg is capable of acting as a breakwater because of the extensive area which it covers, and the great depth below the water surface to which it extends.

Its area being sufficient to cover several waves, it floats at the normal water-level. This it does in the heaviest seas, which, great as they may be, are small in comparison to its mass, Hence, as it does not accommodate itself to the motion or lift of the waves, they are either reflected from it, or dash themselves against it and are destroyed.

Large vessels, drawing, it may be, 25 to 28 feet of water, when running on a course parallel to the waves, rise and fall to them as they pass, thus allowing them to go on their way unchecked and unaltered.

In order that a vessel should not thus accommodate itself to storm-waves, when broadside on to them, it would be necessary for it to possess sufficient *beam* (say 1500 or 2000 feet, or even more) to cover at least three such wave-crests.

Any one who has watched the behaviour of vessels riding at anchor in a heavy sea cannot fail to have noticed how greatly the movements of the larger and smaller ones differ. A long vessel, riding head to wind, is comparatively steady, because she spans, it may be, the whole or the greater part of the distance between two waves, and the several motions of the wave-particles, acting upon her hull, neutralize each other. A smaller vessel, on the other hand, whose length, let us suppose, does not exceed one-third that of a wave, is seen to range backwards and forwards, and up and down, as each wave passes. Such a vessel, when in the trough of the sea, is to some extent sheltered from the wind, and she advances with the water-particles towards each on-coming wave (see Fig. 6, p. 25). At such times her cable, being to a considerable extent relieved of strain, sags and becomes slack. When, however, the vessel is riding on the top of a wave, not only is the motion of the water-particles reversed, but she is exposed to the full force of the wind, and, with her bows high in the air, she is hurled back with tremendous violence, her moorings at such times being often tried to the uttermost. The vessel thus advances and is driven back, and rises and falls in obedience to the motion of the water-particles, but the waves themselves are not reduced or altered in any way.

From the foregoing, it may, I think, be gathered that a floating structure—it would not be correct to call it a breakwater—of indefinite length, but having a *width* of, say, 100 to 150 feet, exposed to waves of 400 or 500 feet in length, *i.e.* crest to crest, would behave in much the same way as the smaller vessel we have been considering; but, inasmuch as the fine stem and bows of the vessel would be represented by the bluff face of the structure, I leave the reader to imagine what kind of moorings would be required to hold it.

The idea of a floating breakwater with a width sufficient to span from crest to crest of even two long storm-waves is absurd, and need not, therefore, be considered.

There can be no doubt that a floating structure, capable of acting as a breakwater in a heavy sea, must be of such gigantic proportions as to render its construction, as well as its mooring, practically impossible. Small surface waves might be stopped by a correspondingly smaller structure, but these would probably be unobjectionable if allowed to pass.

A boat alongside and under the lee of a large ship riding broadside on to the waves derives shelter from surface lipper; but, in even a moderate sea, it ranges up and down against the side of the ship to almost, if not quite, as great an extent as if it were on the weather side of her.

On more than one occasion, it has fallen to my lot to have to scramble up the lee side of mail steamers, lying at anchor off some of the Cape ports, during a strong breeze or moderate gale from seaward, while the lighter which conveyed me from the shore—a boat of about 100 tons burden—was ranging up and down to the extent of fully 10 or 12 feet. These steamers measured from 350 to 400 feet in length, and drew from 22 to 23 feet of water.

Few persons, after a similar experience, would have much faith in floating breakwaters.

The ocean steamers at the ports to which I refer, are obliged to lie at anchor in the Agulhas current, which is sufficiently strong to swing them round almost broadside on to a strong breeze from seaward. During strong gales they are often obliged to steam up to their moorings in order to relieve the strain upon them, and at times they are obliged to slip their cables and put to sea.

Booms of timber are sometimes used in small harbours to prevent the range passing from one basin to another. In such cases the ends of the booms are fitted into grooves in the side walls of the entrances or passages, and boom is placed upon boom until the lowermost one touches the bottom.

It is found that if the booms do not extend to the bottom, the undulations are communicated from one basin to the other underneath them. This being the case where the height of the undulations may be measured by inches, what hope of success could there be in attempting to stop an ocean roller by a floating structure?

As regards the floating-weed type of breakwater, I cannot do better than quote from the "Supplementary Report of the Royal Commission on Harbours of Refuge, 1859"—

> "A plan of a floating breakwater has been proposed by Vice-Admiral Sir George R. Sartorius. This consists of three parallel lines of buoys placed diagonally, the space between each buoy being about four times its diameter, and the distance between the lines about 30 or 40 yards, each buoy being separately moored with chains and anchors. A floating band of matting, 20 yards wide, is to be extended within the lines of buoys, and to be secured by anchors.

"A triple line of buoys, of a mile in length, each buoy 16 feet long by 9 feet in diameter, so moored, would require 400 buoys, and if moored with two anchors, as proposed, in a depth of eight fathoms, and with a scope of chain each way equal to three times the depth of water, each buoy would require 50 fathoms in length, or 20,000 fathoms of chain, and 800 anchors for each mile in extent.

"The experience of the Trinity House shows that chains require to be shifted once in four years, and as the cost of a buoy and chains would be about £250, the expense of materials alone, without the labour of mooring, would be at the rate of £100,000 a mile.

"Independently of the cost and want of durability, we are of opinion that the buoys, even with the addition of the matting, would not reduce the main undulation of the waves; nor is it by any means certain, with spaces between them equal to four times the diameter, that they could reduce the surface sea to any great extent. The buoys, too, if hollow, might in a dark night be perforated by an enemy and sunk, or they might be cut adrift."

The designs for floating breakwaters which have come under my notice have been of so unpractical a character that it would serve no useful purpose to describe them; but even supposing a structure of this kind to be practicable, a most serious objection to its adoption would be the extreme risk to which vessels lying under its lee would be subjected in the event of its breaking adrift during a heavy on-shore gale—by no means a remote contingency.

Notwithstanding the extra precautions which are taken in mooring lightships, of say 150 to 180 tons, at sea, it is no uncommon occurrence for them to drag their moorings, although they often find it necessary to veer to 180 fathoms of cable.

In the evidence given before the committee appointed by the Board of Trade to inquire into the desirability of establishing electrical communication between light-vessels and the shore, it transpired that one great difficulty in connection with this was the swinging of the vessel, which occasioned kinks and twists in the electric cable.

The chairman, examining Sir James N. Douglass, late engineer-in-chief to the Trinity House, asked, "Am I right in supposing (I have heard it said by persons, possibly not qualified to judge) that, in order not to allow a cable to kink in any way, you ought to moor the light-vessel head and stern, and not allow her to swing to the tide? Do you think that possible, in the first place?"

Sir James N. Douglass replied, "I look upon it as a simple impossibility to moor any elongated vessel head and stern in a tideway at sea."

CHAPTER XIV.

DIFFERENT METHODS OF CONSTRUCTING BREAKWATERS.

Staging—Barges—Cranes or over-end setting machines—Facilities afforded by staging in constructing rubble-mound breakwaters—Holyhead breakwater staging—Sea-staging of ordinary type—Mode of depositing rubble at Holyhead—Mode of constructing Alderney breakwater—Aberdeen breakwater staging—General remarks on staging—Facilities afforded by staging in building block-work, etc.—Cost of staging—Rubble mounds formed by means of barges—Advantages of steam-barges—Bags of concrete, also concrete blocks, placed by barges—Barges and staging compared—Various types of setting machines—Block-lifting appliances—Diving—Mound breakwaters constructed by over-end tipping.

Several of the methods usually adopted in constructing breakwaters have already been referred to, and some of what may be called the secondary appliances have been described with sufficient minuteness.

The various devices for constructing breakwaters differ, as will have been gathered, very widely from each other; but the systems commonly adopted may be generally classified under three heads, viz. staging, barges (with or without shears), and cranes or over-end setting machines.

Staging is applicable alike for depositing rubble, laying bag-work, putting in mass-work, setting blocks, or building masonry; but the question whether a stage is the best to employ in any individual case must, in common with other systems, depend upon circumstances.

Barges are frequently used for depositing rubble in mounds where the depth of water is sufficient to admit of this being done. They are also used for depositing bag-work, as well as blocks of concrete in pell-mell work. When used for this latter purpose, they are usually, though not always, provided with powerful shears.

Cranes, or Over-end Setting Machines, are used for setting blocks and building masonry, also for putting in mass-work and bag-work, and depositing blocks—pell-mell—in wave-breakers.

In constructing the breakwater at Leixoes, in Portugal, an exceptionally large "Titan," with a maximum working radius of 144 feet, was used for depositing rubble in the mound ahead of the built work; but this is unusual, and in many cases would not be a desirable system to adopt.

Staging.—Amongst the many breakwaters which have been constructed from staging, those at Holyhead, Portland, Dover, Table Bay, Ymuiden, Alderney (in part), Hartlepool, and the south breakwater at Aberdeen, may be cited as examples.

The facilities afforded by staging for depositing rubble to form the mounds of breakwaters are very great. This fact was fully recognized during the construction of the Portland breakwater, insomuch that after the completion of its landward section, which had a length of about 1700 feet, and which would have afforded excellent shelter for barges, had it been desired to use them, the same system of depositing from a stage was adhered to for the outer isolated breakwater, which was 6400 feet in length, and this notwithstanding that an opening between the end of the shore breakwater and the commencement of the outer breakwater had to be left. Although this opening was only 400 feet in width, it necessitated the construction of a bridge, or extra strong length of staging, measuring about 1000 feet. This may, therefore, be viewed as a parallel case to constructing, by means of staging, an isolated breakwater 1000 feet distant from the shore.

By the use of staging in constructing rubble-mound breakwaters, work may be carried on uninterruptedly in almost all weathers, thus giving constant employment to all those engaged upon it, and effecting a large saving in cost.

If stone cannot be readily disposed of, the quarry soon becomes blocked, and plant, including that used in conveying the stone from the quarry to the breakwater, lies idle, whilst the return for wages is practically *nil.*

Another advantage possessed by staging is the facilities which it affords for ascertaining the level and line of the rubble as the formation of the mound proceeds, and also for depositing rubble of various classes on defined lines, if such should be

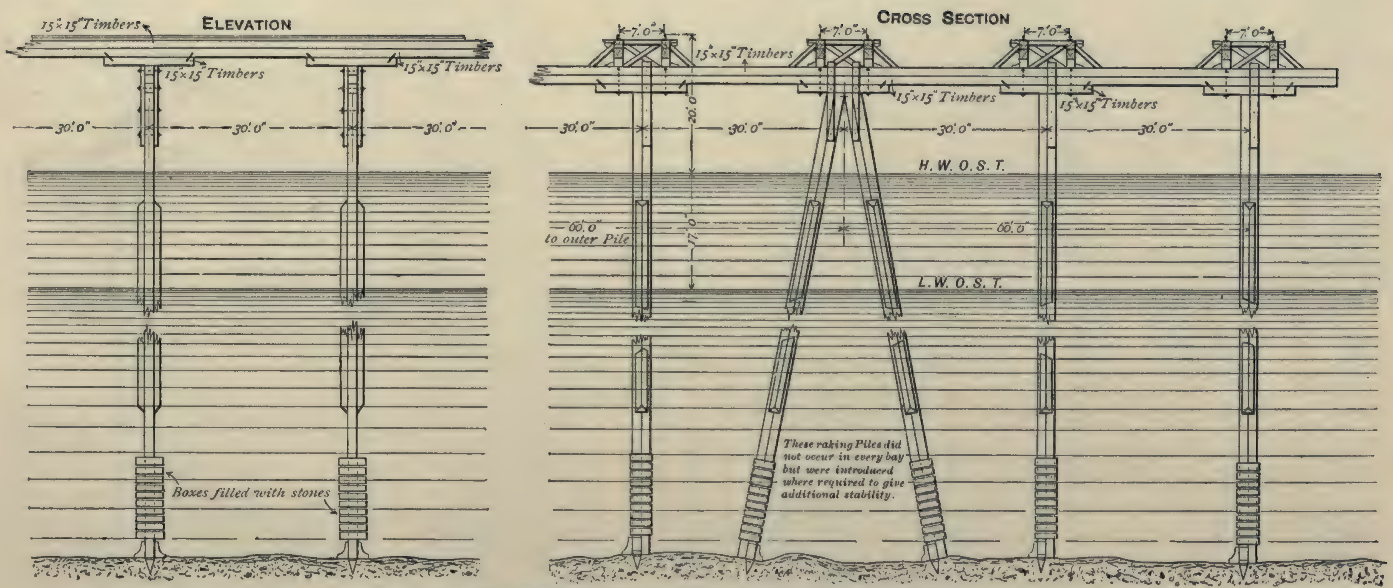


FIG. 60.—Staging as used in constructing the breakwater at Holyhead.

These raking Piles did not occur in every bay but were introduced where required to give additional stability.

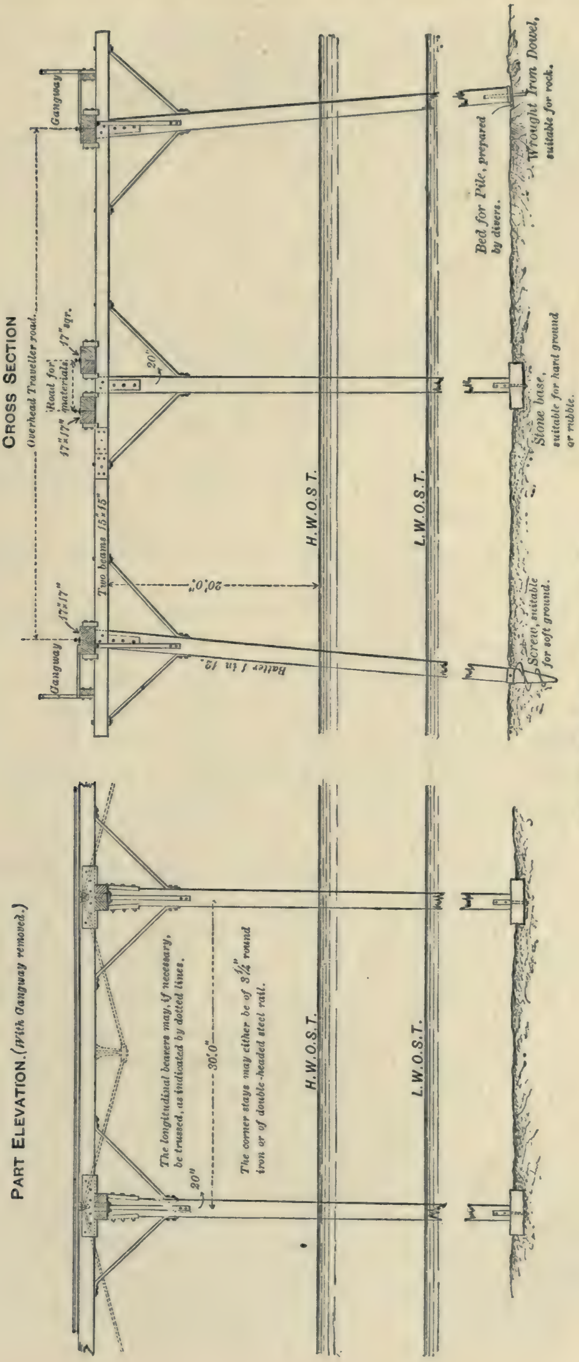

CROSS SECTION
(Overhead Traveller road.)
Gangway
Gangway
Road for materials.
17" sqr.
17"x17"
17"x17"
Two beams 15"x15"
20'0"
20"
Batter 1 in 12.
H.W.O.S.T.
L.W.O.S.T.
Bed for Pile, prepared by divers.
Wrought Iron Dowel, suitable for rock.
Stone base, suitable for hard ground or rubble.
Screw, suitable for soft ground.
PART ELEVATION. (With Gangway removed.)
The longitudinal bearers may, if necessary, be trussed, as indicated by dotted lines.
20"
30'0"
The corner stays may either be of 3½" round iron or of double-headed steel rail.
H.W.O.S.T.
L.W.O.S.T.

FIG. 61.—Sea-staging, ordinary type.

required. The staging used in constructing the Holyhead breakwater is shown in Fig. 60, p. 238.

In order to comply with special requirements, the number and spacing of the supports, as well as the arrangement of the roads, necessarily varies in almost every stage; nevertheless, a strong family likeness is noticeable in many of the stages which have been used for constructing sea-works during recent years.

The principle of construction illustrated in Fig. 61, p. 239, has been extensively adopted, and has in most cases proved satisfactory. The stages used in constructing the breakwaters at Dover, Alderney, Douglas, Ymuiden, and Hartlepool were all more or less after this pattern. At Ymuiden and Hartlepool, the central row of piles was omitted, and the cross-timbers, or sills, connecting the two outer rows were strengthened by trussing; while at Alderney and Douglas an additional row of piles was introduced.

The arrangement for discharging the rubble from the waggons at Holyhead was as follows:—

The staging carried five lines of railway, running parallel to each other. These were spaced 30 feet apart, centre and centre, and their gauge was 7 feet. This wide gauge was adopted in order that the rubble might be discharged from the waggons between the longitudinals carrying the rails. The waggons were of peculiar form, and were designed by the late Mr. G. M. Dobson, when resident engineer on the Holyhead harbour works. The sides were fixtures, but the bottom, which was in the form of a huge coal-scuttle, was supported by trunnions so arranged that when the waggon was empty the bottom, being heavier behind than in front of the trunnions, came up and closed of its own accord; whereas when the waggon was loaded, the weight forward of the trunnions was the greater, and caused the bottom to tip when catches underneath the waggon were released.

At the point where it was desired to discharge the rubble into the sea, two tumbling blocks were fixed. These disengaged the bottom catches of the waggons as they passed over them, thus causing the contents of the waggons to fall into the sea. As soon as the contents of a waggon were discharged, the bottom of the waggon fell back into its place, and the catches into theirs, the waggon being thus again ready for filling. The whole process was automatic, and worked admirably.

The rubble forming the mound was carried up to the level of 8 or 10 feet above high water, a series of parallel longitudinal banks or ridges being formed under the several lines of railway. These were levelled down, and the mound consolidated by the action of the sea, additional rubble being deposited from time to time, as was found to be necessary. After a sufficient time (usually from four to five winters) had elapsed to admit of the thorough consolidation of the mound, a trench was excavated along it, down to the level of low water of spring tides, to receive the masonry of the superstructure.

In the Alderney breakwater, the stone forming the mound was, with the exception of a short length at the commencement, deposited from hopper barges, varying in capacity from about 60 tons to 140 tons each; but a staging was erected upon the mound for use in building the superstructure. On account of the exposure of the site, this staging had to be removed at the end of each working season, and re-erected at the commencement of the next. In general design it resembled that illustrated on Fig. 61, p. 239. The bays each measured 30 feet, and the piles were furnished with flat stone bases, each weighing about 15 cwt. The piles were "pitched" from an outrigger travelling-carriage, and they were surrounded at their bases with rubble stone as soon as possible after they were placed in position. The great depth of water at Alderney, and the exceptionally heavy storms experienced there, afforded good grounds for the subsequent adoption of barges, in preference to staging, for depositing the rubble.

One of the most important considerations in designing a sea-staging is to allow as little material as possible to be within reach of the highest waves. Its roadway should therefore be at such a level as to place it altogether out of the reach of such waves. Experience has shown that this should not be less than from 18 feet to 20 feet above the highest tide in exposed situations around the British coasts. Other considerations in connection with the work to be executed may, of course, necessitate its being placed much higher.

The roadway of the staging adopted by Mr. Dyce Cay, M.I.C.E., in constructing the south breakwater at Aberdeen, was 30 feet above high water of ordinary spring tides, the piles or uprights being of round timbers. The fact that this staging sustained no injury during the whole time that the work was in progress was probably due in a great measure to these features in its design.

Oregon or Dantzic masts are very suitable for stage piles. They are usually placed with the small ends downwards, and are secured in various ways.

In the Portland staging they were, during the first period of the work, shod with Mitchell's screws, and screwed into the sea-bed. Afterwards it was found that attaching a large flat stone to the end of the pile, and merely allowing it to rest on the surface, as was done at Alderney, answered equally well and effected a saving in expense.

Sometimes cast-iron shoes, or sole-plates, are used, varying in size according to the nature of the ground, but generally having an area of from 12 to 16 square feet.

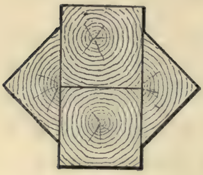


Fig. 62.

In the Holyhead staging, many of the supports were formed of double baulks, securely bolted together and "fished," half timbers being spiked upon them, as in Fig. 62, so as to split and throw off passing waves.

Each pile was weighted by means of a box, which was built round the lower part of it and filled with rubble stone. The bases of the piles, instead of being provided with flat stones, as at Alderney and Portland, had wooden cleats bolted to them. They merely rested on the bed of the sea, and, as in the other cases named, were surrounded by rubble as soon as possible after they had been placed in position (see Fig. 60, p. 238).

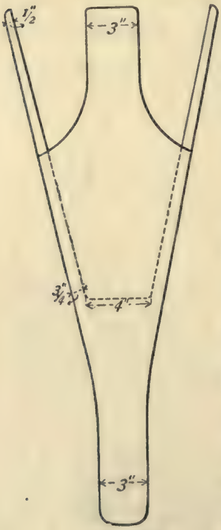


Fig. 63.

Where the sea-bed is of rock, the lower end of the pile is generally hooped with iron, and provided with an iron or steel pin about 1½ or 2 inches in diameter, and projecting 12 or 14 inches beyond the bottom of the pile. This pin is inserted into a hole, which must be drilled in the rock to receive it. It acts the part of a dowel, and so holds the pile in position.

When the surface of the rock is uneven or sloping, a level bed should be dressed for the pile to rest upon; or, should the rock be of a nature to render this difficult or undesirable, the piles may be furnished with shoes fitting into holes formed for them in the rock. Cast-steel shoes of the pattern shown in Fig. 63, and weighing about a hundredweight each, are suitable in such cases.

When ground is too soft to admit of piles merely resting upon its surface, they may either be driven or screwed into it until the necessary amount of support has been obtained.

Lateral support is given to staging by means of chains, which are usually formed of wrought-iron rods, varying from, say, 1¼″ to 1¾″ diameter, with eyed ends coupled by side links and bolts. These are attached to the pile-heads by means of eyebolts, and they are generally made fast either to screw moorings or to anchors weighing about 20 cwt. each, or, where the bottom is of rock, to lewises fixed into it.

The stays are generally tightened up by means of union screws.

Although it is often, or indeed generally, necessary to have recourse to stays, they are objectionable, inasmuch as the waves in a heavy sea take a great hold of them, and cause considerable movement in the staging. For this reason, chains formed of long rods of round iron, coupled together, are preferable to ordinary short link chains.

When it is necessary to build staging piles into the masonry of a breakwater, as is sometimes the case, it is well to allow a clearance of a few inches around them. This prevents the vibration of the stage disturbing the new work, and allows of the piles being protected from the ravages of sea-worms by grouting them up, later on, with cement grout. If this be not done, voids, which may afterwards give trouble, are likely to be formed in the work.

Mr. W. Smith, M.I.C.E., engineer to the Aberdeen Harbour Commission, in describing some damage which had been done to the Aberdeen south breakwater, said—

> "The piles, where they passed through the superstructure, were found to be eaten away by sea-worms, leaving spaces 2 feet in diameter between the blocks.
>
> "The destructive influences bearing on the south breakwater since its construction had been: 1st, the scour on the foundations of the seaward face by the seas coming from the north-east, concentrated by deflection along the side of the breakwater; 2nd, the compression of air in the open joints of the blocks, and in small cavities formed accidentally by disintegration of the surface of the concrete, *by the*

destruction of the piles passing through the concrete blocks by sea-worms, and by the subsidence of the blocks beneath the superstructure of homolithic concrete; 3rd, the disintegration of the surface of the concrete by the chemical action of the salt water on the Portland cement; 4th, excessive pressure on points of the concrete blocks, due to contact of the surfaces without mortar, splitting the blocks; 5th, the abrasion of the sides near the beach by stones, and the smashing of the roadway, parapets, and stairs at the lighthouse tower by the water from spent waves falling off the tower. *The most destructive force was that of compressed air, the other destructive influences being dangerous in the degree to which they laid the breakwater open to the compression of air by the waves.*"[1]

It is not always necessary or desirable that staging should extend from the shore to the end of the work, inasmuch as lengths of it may be "fleeted" or taken up and used over and over again as the work advances, provided that facilities are afforded for running back, or transporting in some other way, the cranes, travellers, and other plant employed on the staging. This may be done either by means of ramps, or by suitably constructed carriages. The latter were employed both at Alderney, and at the Aberdeen south breakwater-works, and were found to work satisfactorily.

Where rubble mounds are of large proportions, as in the Holyhead and Portland breakwaters, the system of depositing the stone from a stage will generally be found the best to adopt; but where a mound is of moderate proportions, and other circumstances favourable, barges may often be employed with advantage, especially in cases where the top of the mound can be kept at a sufficient depth to allow of the barges passing over it at all times of the tide.

Where large numbers of men are employed getting and supplying rubble for a breakwater, it is evident that, should a spell of rough weather put a stop to its being tipped into the sea, the quarry would soon become congested, and the men and plant employed would be thrown idle. In some localities this would mean a complete stoppage of work during the winter months. With a properly constructed staging, having its roadway well above the waves, the chances of such interruptions would be far less than if barges were employed. The question of cost will, however, always be an important factor in deciding all such matters, and this will be affected by the quantity of work to be done per unit of length, seeing that a small mound might require almost as costly a staging as a large one.

---

[1] *Min. Proc. Inst. C.E.*, vol. lxxxvii.

During the construction of the Portland breakwater, the work of depositing rubble from the staging was, on an average, not interrupted, on account of weather, more than from two to three days in a year.

In the preparation of foundations, and the setting of blocks, especially under water, staging offers many facilities.

Work in its various stages may be carried on simultaneously over a considerable length, several machines being employed as against one in over-end work. The overhead plant requisite for dealing with heavy loads may, moreover, be of a comparatively inexpensive character. Temporary platforms for the use of divers, or for other purposes, may be suspended from the stage in almost any position, and the lines and levels of the work may be given and checked with the greatest ease.

Staging is, however, for the most part costly. That used in constructing the Portland breakwater cost about 8*d.* per ton of rubble deposited. At Holyhead it cost about £20 per lineal foot of breakwater, or 5*d.* per ton of stone deposited. Its use, moreover, almost always involves considerable sea risk, and if the work should be long in hand, the teredo and other sea-pests will have to be reckoned with. The advantages of staging, are, however, so great, that they will, in many instances, be found to outweigh its shortcomings.

Barges.—When hopper-barges are employed for depositing rubble in the sea, shoots, down which the stone is tipped from suitably constructed waggons, are usually fixed at the loading-berths. When, however, the stone is of large size, it is necessary to employ cranes for loading it, in order to prevent injury to the barges by the falling of such heavy weights. In such cases it is convenient to have the bodies of the waggons so arranged that they may be lifted off their under-frames. They thus form large skips, which, together with their contents, may be lowered into the barges, the stone being discharged by means of a tripping-chain. In this way the slinging of stones by means of chains is avoided, and much time is saved. The size of barges commonly used for this work varies from about 60 to 120 tons.

For the guidance of those in charge of the barges, the position for the deposit of the stone on the line of the breakwater is indicated by means of leading marks on the land, or on the finished portion of the breakwater, and also by means of buoys afloat.

In order to prevent undue irregularity in the surface of a mound upon which a superstructure has to be built, care is necessary in depositing the stone; otherwise the cost of levelling it, which must be done by means of divers, will be unduly large.

When it is intended to place a superstructure upon a mound, the latter should be extended well in advance of the rest of the work, so as to give it as long a time as possible to consolidate. In this way the amount of settlement, after the superstructure has been built, will be reduced to a minimum.

An interval of at least one year should be allowed to elapse from the deposit of the rubble to the commencement of building operations; and if this period can be extended to two or three years, so much the better.

When barges are employed, it is evident the mound may be extended as far in advance of the superstructure as is desired, without incurring any such additional cost and risk as a corresponding extension of staging would involve. When, however, a mound is to be raised above the level of high water, or, indeed, to such a level as would interfere with the barges passing freely over it, they can only be employed—if at all—to supplement the deposit of the rubble by other means.

By the use of barges, where applicable, the risks appertaining to staging are avoided; but others, scarcely less formidable, are often incurred, and the prosecution of the work is greatly dependent upon the state of the weather.

Barges used for depositing rubble are generally constructed with hopper bottoms, through which the rubble is discharged; but when a mound is to carry a superstructure founded below low water, the last two or three feet of its height should be brought up by selected stone thrown overboard by hand. In this way the surface of the mound may be formed to a fairly level and regular plane whereby the labour and cost of preparing the foundations for the superstructure by means of divers will be considerably reduced.

Steam-barges, as illustrated on Fig. 64, are preferable to ordinary barges towed by tugs, because they are better under

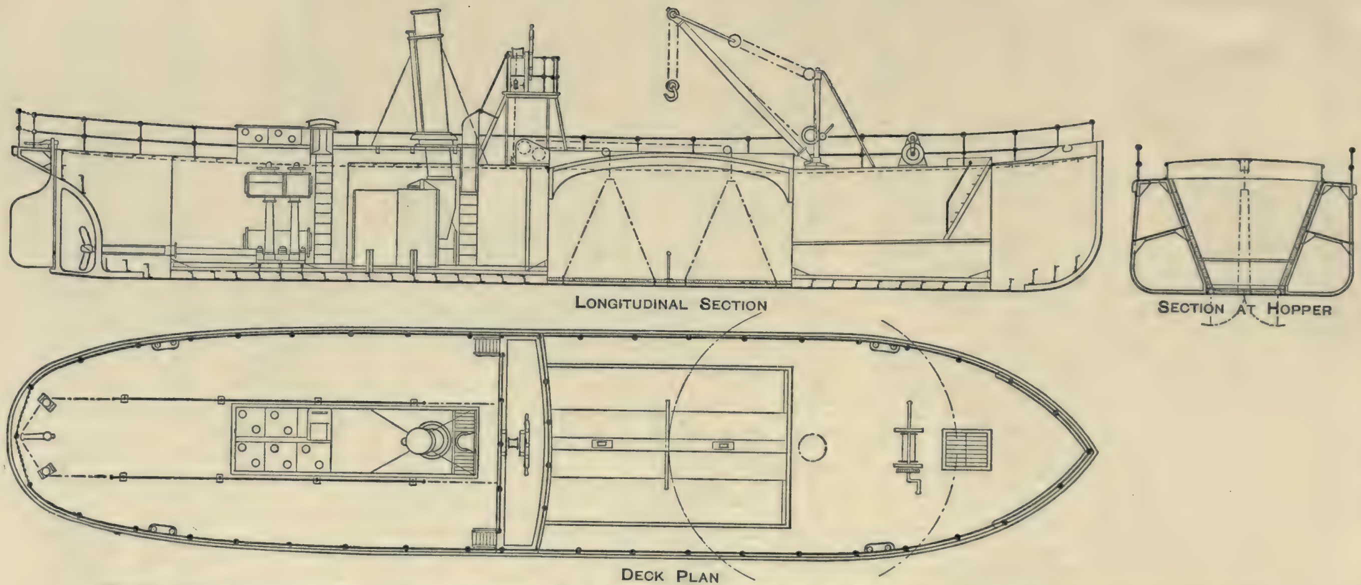


FIG 64.—100-ton steam hopper barge.[1] Dimensions—length, 90 feet; breadth, 18 feet; depth, 9 feet. Mean draft in working trim when unloaded, 5 feet; ditto loaded, 7 feet. Nominal horse-power of engines, 25; indicated ditto, about 150.

---

[1] From drawing supplied by Messrs. Wm. Simons & Co., Renfrew.

control, and can be more easily placed in position when depositing material.

Barges, somewhat similar to those employed for depositing rubble, are used for laying concrete bag-work foundations. The bases of the breakwaters at Aberdeen (north pier), Fraserburg, and Newhaven (Sussex) were formed in this manner (pp. 188 *et seq.*).

Barges are also employed for depositing the blocks used in constructing breakwaters of the pell-mell type. So long as the surface of the mound is sufficiently low to allow of the barges floating over it, the blocks may either be dropped through the hopper bottom—in which case the depth must be sufficient to admit of the blocks so dropped clearing the bottom of the barge—or they may be launched from the barge decks, which should be formed to a suitable inclination, and provided with convenient appliances for holding the blocks in place and releasing them when required.

Sometimes, instead of the blocks being dropped or launched as just described, they are suspended from a beam resting upon two barges or pontoons, and are thus floated into position.[1] When conveying blocks in this way, their weight is greatly reduced by allowing them to remain immersed.

When the mound becomes too high to admit of barges passing over it, the blocks must either be cast *in situ*, or be placed in position by means of floating shears. A drawing of one of the 25-ton barges, fitted with shears, which was used for this purpose in constructing the breakwater at Alexandria, is given in Fig. 65.

It is not always easy to satisfactorily compare the relative advantages of staging and barges; but the following are some of the principal points which require consideration:—

(1) First cost and maintenance.

(2) Cost of quay or stage whereat to load the barges.

(3) The provision of adequate shelter for all floating plant.

(4) Working expenses of floating plant, also of cranes and other appliances for loading the barges.

(5) Sea-risk.

(6) Relative amount of work which can be done by the two systems in a given time.

---

[1] Blocks weighing from 200 to 300 tons were conveyed and deposited in this way in constructing the South Gare breakwater, at the mouth of the River Tees (*Min. Proc. Inst. C.E.*, vol. xc, p. 352).

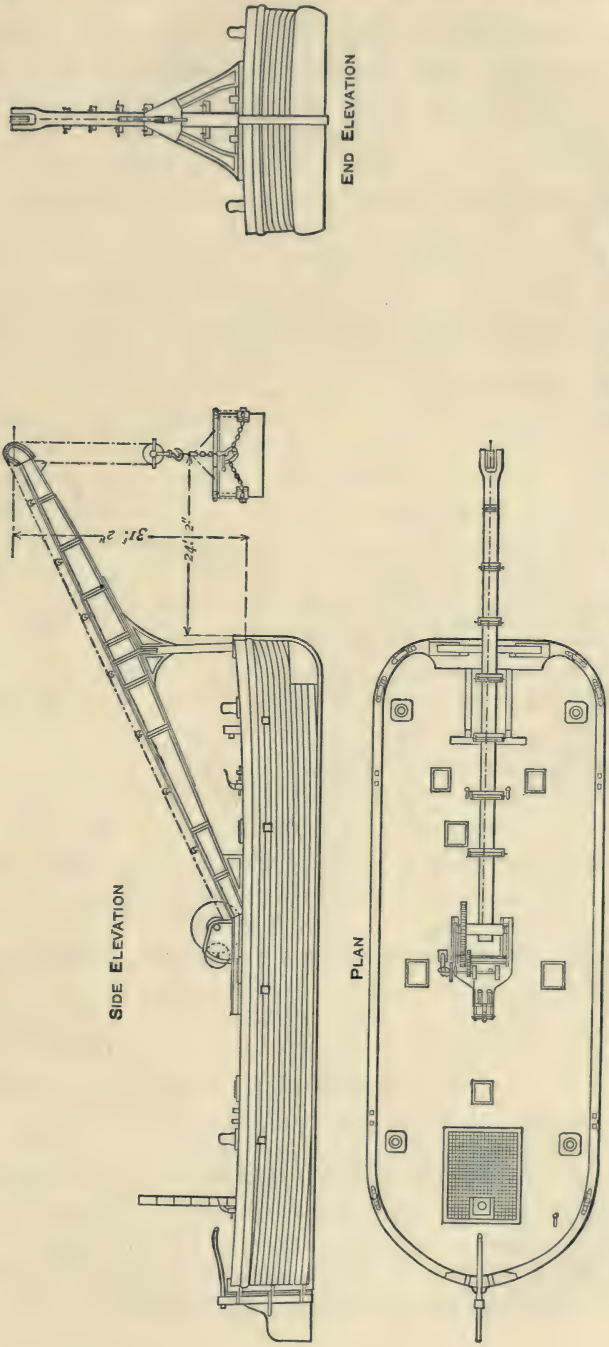


Fig. 65.—25-ton derrick barge, as used for depositing concrete blocks in Alexandria breakwater. Length, 86 feet; breadth, 30 feet.

Cranes or Setting Machines.—The system of constructing vertical-built piers from staging has, to a great extent, been superseded of late years by the use of powerful machines with long overhanging arms. Whether this is desirable in every case is a matter which each engineer must decide for himself.

Setting machines necessarily vary in design according to the nature of the work they are required to perform. The larger kinds of them are known by fanciful names, such as "Hercules," "Titans," "Mammoths," and so forth. They all travel upon rails laid on the finished portion of the breakwater, so that they can follow up the work as it advances; or, when necessary, be run back into a place of safety.

Some of these machines have longitudinal and transverse motions only, the overhanging portion, or main arm, being provided with a travelling carriage with cross-motion of sufficient scope to admit of its commanding the full width of the breakwater.

This type of machine was used in constructing the breakwaters at Mormugão, Colombo, Kurrachee, and at some other places; and for facility of setting blocks within its range it is superior to either the "radial" or "all-round" types. Its comparatively small transverse range is, however, sometimes found to be a drawback, inasmuch as outlying work, such as aprons, etc., cannot be commanded by it.

One of these machines is represented in Fig. 66.

In radial machines, the movable arm is pivoted upon the fore-end of the under-carriage, the "tail-end," which carries the engines and balance-load, being supported by rollers running upon a suitable path, fixed at the after-end of the carriage.

The truck, or "jenny," in these machines has no transverse motion, but merely travels in and out upon rails fixed upon the radial arm.

The transverse range of these machines is usually sufficient to enable them to place blocks and bag-work in aprons of ordinary width, and, unless something abnormal is required, they afford all necessary facilities. Unless, however, they are constructed to travel with their load—which in the larger class of machines is not usual—they cannot work so near to the scar-end of a breakwater as "all-round" machines, because room must be left for bringing blocks to the front within range of the "jenny." A portion of their overhang is thus rendered ineffective, a point in which "all-round" machines have a decided advantage.

An excellent machine of the radial type, capable of dealing with working loads of 50 tons at a radius of 109 feet, is now in use at the breakwater which is being constructed under the direction of Mr. H. H. Wake, M. Inst. C.E., at the mouth of the River Wear.

Machines of the "all-round" type are, as their name indicates, capable of revolving around the entire circle. Ordinary long jib travelling-cranes are of this type, and for constructing small piers they are very efficient and comparatively inexpensive.

In machines of the larger class, the movable arm is usually made horizontal, being either formed of rigid cantilever girders, or of lighter longitudinals supported at two or three points along their length by tie-rods attached to, and extending from, the top of a central rigid post or frame. Type-sketches of these machines will be found in Figs. 67–69, p. 252.

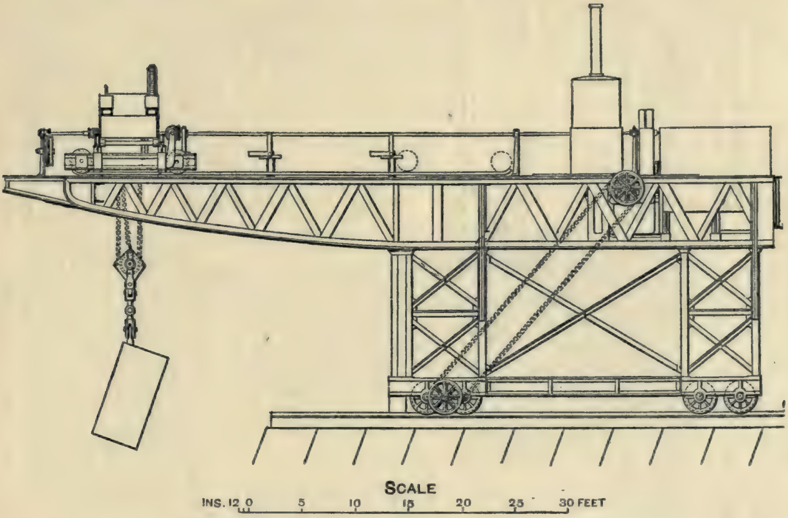
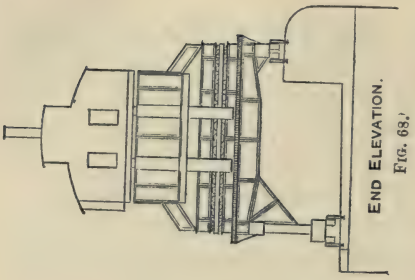


Fig. 66.—Block-setting machine as used at Mormugão.[1]

In machines of this class, the movable arm usually revolves upon a number of rollers fixed in a frame, forming what is technically known as a "live ring," and the design, generally, very much resembles that of a swing bridge mounted upon an under-carriage. The "jenny," as in the case of radial machines, travels upon the top of the movable arm, and has no transverse

---

[1] *Min. Proc. Inst. C.E.*, vol. xcvii.



End Elevation.

Fig. 68.

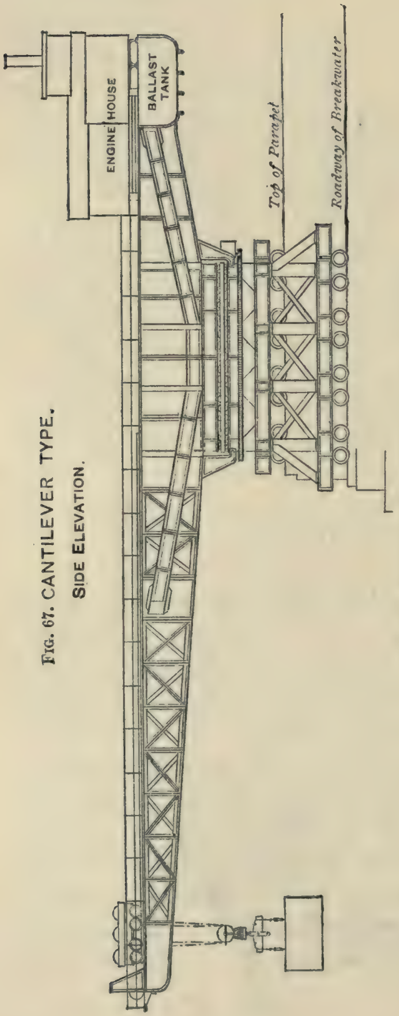


Fig. 67. CANTILEVER TYPE.

Side Elevation.

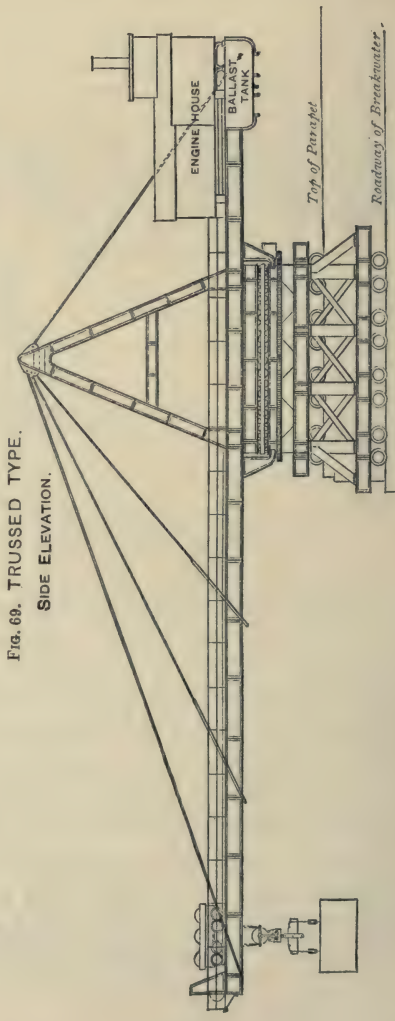


Fig. 69. TRUSSED TYPE.

Side Elevation.

Type-sketches of all-round block-setting machines.

motion other than that imparted by the movement of the main arm.

A large machine of the rigid cantilever type, capable of dealing with working loads of 50 tons at a radius of 100 feet, is now in use at the Harbour of Refuge works at Peterhead, N.B.; and two machines of the braced type, of somewhat similar power and dimensions, which were designed by Mr. P. J. Messent, M. Inst. C.E., have been employed for a number of years at the mouth of the River Tyne, constructing the piers there under his direction.

The setting of blocks or the laying of bags, either by a "radial" or "all-round" machine, is not so easy as with one having only longitudinal and transverse motions, inasmuch as, excepting when the main arm of the machine is parallel to the centre line of the work, the load moves diagonally, and when adjusting its line in one direction it is thrown out in another. This feature is especially inconvenient in setting work under water, where it is out of sight.

The range or overhang of a setting machine must necessarily depend to a great extent upon the design of the work upon which it is to be employed; but it will be found convenient to have it sufficiently large to lay three or four tiers of the bottom course of blocks in advance of the scar-end, because the blocks can, in this way, be laid and levelled with greater facility and regularity than when an advance of only one block at a time is made.

Block-setting.—When blocks are to be used in built work, they are generally lifted by means of T-headed bars (Fig. 71, p. 254). These pass through oblong holes, terminating in recesses at the bottom of the blocks. The object of these recesses is to allow of the bars being turned round, so that the T-heads may take hold of the blocks, as in Fig. 70. After a block has been set, the bars can be released immediately by giving them a quarter-turn.

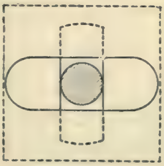


FIG. 70.

When blocks are large, it is necessary, in order to prevent the concrete being crushed by the T-heads, to build into them pieces of finely dressed hard stone, or of hard wood or iron for the T-heads to bear upon.

In blocks for sloping coursed work, the holes for the lifting bolts should be placed at such an angle that the block, when suspended, will hang at the required inclination (Fig. 66, p. 251). Sometimes long tapered lewises are used instead of T-headed bars; but blocks are liable to be split by them, and they are therefore not desirable.

Large washers and nuts have in some instances been built into blocks, the lifting bars being screwed into them for lifting.

Fig. 71.

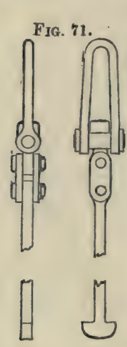


Fig. 72.[1]

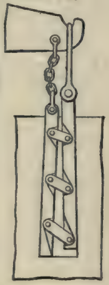


Fig. 73.

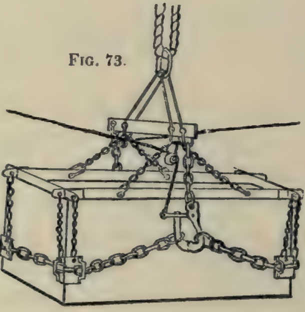


Fig. 74.[1]

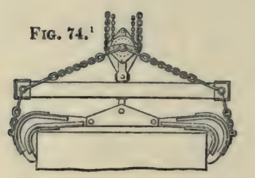


Fig. 75.[1]

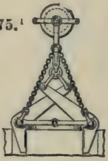


Fig 76.[1]

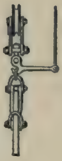


Fig. 77.[1]

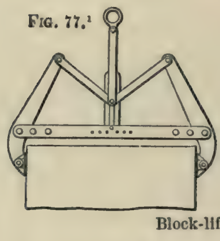
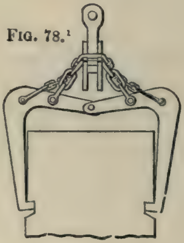


Fig. 78.[1]



Block-lifting appliances.

and unscrewed and withdrawn when the blocks have been set. This plan has several drawbacks, not the least of which is that all the washers and nuts are lost, as they cannot be got out of the blocks.

Some other block-lifting appliances are illustrated in Figs. 72–78.

---

[1] *Min. Proc. Inst. C.E.*, vol. cxiii. part iii.

When it is required to drop blocks or deposit them irregularly, as in pell-mell work, whereby the withdrawal of T-bars or lewises would be rendered difficult, one or other of the methods represented by Figs. 73–78 may be adopted. That illustrated by Fig. 73 was used in depositing the blocks forming the Alexandria breakwater; and that illustrated by Fig. 74 is now being used for placing the wave-breaker blocks in the Madras breakwaters.

Concrete blocks are usually made upon a level floor in some convenient situation, and when required for setting in the work, they are loaded upon trucks by means of an overhead traveller or "Goliath." On arriving at the breakwater, they are lifted by the setting machine and placed in the work.

Diving.—The preparation and levelling of the beds, and the setting of blocks below low water, necessarily requires the aid of divers. Some engineers prefer the diving-bell to the helmet for under-water work; but when circumstances will admit of helmet divers being employed, more work can as a rule be done in a given time than when a diving-bell is used.

At the Dover (Admiralty) pier, the number of blocks (averaging 6 to 7 tons each) set in a "shift" of 4 hours by means of the diving-bell was four, or at the most five. By the introduction of diving dresses and helmets, the number was increased to 8. Where a strong current existed, however, the bell was found to have an advantage over the dress; indeed, work could be executed from a bell under conditions where a diver in a dress could not stand. When the velocity of a current exceeds three miles per hour, helmet diving becomes very difficult, and the strain on the life-line and air-pipe is excessive.

At the Alderney harbour works the use of diving-bells was given up, and helmet divers substituted, the reason assigned being that when the bell was lifted a little off the bottom, the rapid current drove the men against the sides of it.[1] It would appear, however, that the conditions at Alderney must have been exceptional, inasmuch as the experience there seems to have differed from that at most other places. It is difficult to understand how helmet divers, with their whole bodies exposed to the force of the current, could have worked better than men who were to a great extent protected from it by the bell.

Over-end Tipping.—Mound breakwaters are sometimes made by tipping the material over-end in the same way that a railway embankment is formed. When this is done, the bank must be kept at such a height above high water as to admit of lines of railway being laid along it.

---

[1] *Min. Proc. Inst. C.E.*, vol. xxxvii. p. 361.

This system is only applicable where the exposure is not great. In a work exposed to a heavy sea, the expense resulting from the displacement and washing away of the lines of way would probably equal or exceed the cost of staging, especially if the delays arising from such interruptions were taken into account.

The mound portion of the sea-wall at Port Elizabeth (Cape Colony) was formed in this manner. It was nearly broadside on to the waves, and was composed of rubble and concrete blocks varying in weight from 7 tons downwards. The depth of the water along the face of this bank did not usually[1] exceed 11 or 12 feet at high water; nevertheless long lengths of rails and sleepers were often displaced, necessitating much labour in making up the bank, and recovering, straightening, and re-laying the rails, etc.

Probably the largest breakwaters that have been formed in this manner are those at the mouth of the River Tees. They are composed of blocks of slag weighing about 3 tons each, obtained from the iron furnaces of the district. The rubble forming the breakwaters at Kingstown was also deposited in this way.

The over-end system is well adapted for river embankments or training walls where the exposure is small.

---

[1] The sea-bed was of sand, and its level varied considerably, according to the state of the weather.

CHAPTER XV.

FOUNDATIONS.

Founding upon rock—Difficulties attending execution of work near low water—Benching rock—Steeply inclined strata—Advantages of staging as compared with over-end machines in preparing foundations—Under-water mass-concrete foundations—Levelling foundations with small broken stone—Grouting—Founding upon sand—Curved profiles—Mud—Pilework foundation—Founding upon gravel—Founding upon clay—Founding upon rubble mounds.

VERTICAL breakwaters, with which we may for the present associate the upright superstructures of breakwaters of composite types, are, more than any others, dependent for their stability upon the excellence of their foundations. These should, therefore, be prepared with exceptional care, and without stint of time, labour, or material, so far as the same may be requisite for rendering them as perfect as possible.

Rock Foundations.—Rock is generally held to be the *beau ideal* of a foundation; but rock foundations are often very treacherous, and they are, moreover, beset with difficulties, some of which we will notice shortly.

In preparing a rock foundation within the tidal range, where the surface is too irregular or too hard to admit of being easily dressed to the required level, one or other of the systems illustrated below may be adopted. For convenience of reference, we will call these System A and System B respectively.

CONCRETE FOUNDATION.

System A.

In this system the rock is roughly dressed and levelled to receive a course of face stones. These should be squared and well bedded in cement mortar.

In situations where the tide will quickly reach the new work, either Medina or Roman cement, or a mixture composed of one part of Medina to one or two parts of Portland cement, should be used in preference to plain Portland cement mortar, all joints being pointed as quickly as possible with neat Medina cement.

The face-stones may be made of various thicknesses if desired, so as to minimize the amount of rock cutting. When the setting of these has been satisfactorily accomplished, the space between them may be filled with rich concrete of either Portland or Roman cement, as the necessities of the case may require, rough rubble stone being incorporated.

The surface should then be carefully finished off, so as to resist the fretting action of the waves when the tide reaches it.[1] I have found no system answer so well as that of roughly pitching the whole surface with flat-topped stones of a size that can be easily handled. These should be well worked down into soft concrete, until the latter rises to within about half an inch of their surface. The spaces between them should then be filled with freshly mixed Medina cement mortar, trowelled over so as to render its surface as smooth and regular as possible. Abrupt irregularities should be avoided, as they cause small eddies and overfalls, which are very trying to the newly formed skin.

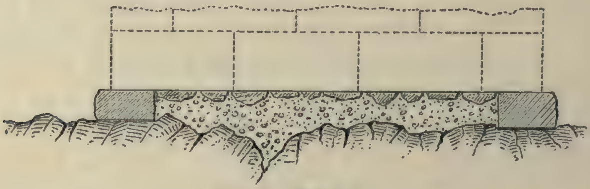


FIG. 79.—System A.

Work finished off in this manner, with due care, if allowed from 10 to 15 minutes to harden before the tide reaches it, will generally be found to stand well; but in all such work there is an element of sea-risk, proportionate to the exposure of the site, which no amount of care can entirely eliminate.

System B is similar to System A, excepting that the squared stones are omitted, and the levelling of the rock surface is thus rendered unnecessary.

---

[1] If good Roman cement concrete be used, it should be able to take care of itself.

CONCRETE FOUNDATION.

System B.

Wrought-iron pins or bars, provided with eyes for the reception of bolts or coach screws, are let into the rock at intervals of about 5 or 6 feet, as shown in Fig. 80, and to these are attached temporary planks, roughly cut to fit the inequalities of the rock surface. The upper edges of these planks are set to the required level, and the concrete is then deposited between them. Should the planking be more than from 15 to 18 inches in height, stays will be required to enable it to withstand the thrust of the soft concrete, and the action of the waves. Cement-bags filled with sand, laid against the boarding, will often be found to give the amount of support required.

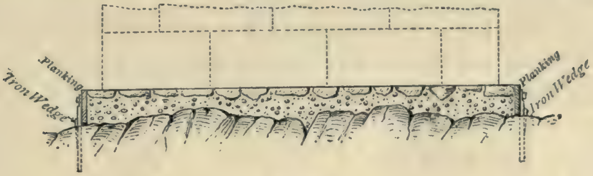


FIG. 80.

In order to prevent undermining, any spaces which may exist between the bottom of the planks and the rock surface should be stopped with Medina or Roman cement. If this be not done, jute canvas should be nailed along the lower edge of the planks, on the inner side, and it should have sufficient width to underlie the concrete for a distance of 12 or 15 inches. Should several tiers of planks be used, the joints must be made water-tight, or they must be covered with canvas so as to protect the concrete until it has set.

The surface of the concrete should be finished off in the manner described for system A.

Instead of a topping of flat stones, pointed with Medina or other quick-setting cement, the surface of the concrete is sometimes covered with jute sacking, weighted down by pieces of iron rails, or in some other way.

When the weather happens to be favourable, and the chafing action of the waves is not great, this system answers well; but should the rails be displaced—as is too often the case—and the sacking become loose, the chafing to which the newly deposited concrete is subjected by the moving rails and the loose canvas is pitiable to see. In such circumstances I have sometimes wished that a wave would clear all the rails and canvas away and leave the concrete to take care of itself.

On one occasion I covered the canvas with boiler-plates $\frac{5}{8}$ inch thick, feeling confident that they would not be displaced as they possessed considerable weight, and there appeared to be nothing for a wave to take hold of. On the following morning, however—a moderate sea having got up during the night—I found that they had not only been displaced, but that some of them had been carried away altogether.

At low water there is frequently a considerable interval of "slack," during which the water-level remains almost stationary. It follows, therefore, that newly mixed concrete put in at or near that level will be subjected to an undue amount of fretting by the waves. The same might happen at or near high water, but work put in at that level can generally be allowed more time to harden, before the water reaches it, than it is possible to give to work near the low-water level. At intermediate levels, excepting in places where the tidal range is very small, the water, after reaching the work, soon covers it, and the fretting action of the waves is thus quickly reduced. Even a single foot of water over new work seems to have a magical effect in checking the chafing action of small waves.

Notwithstanding the foregoing facts, it is not uncommon, in designs for sea-works, to find mass-work stopped within a few inches of low water of spring tides, for the bedding of what is called the "low-water course." Experience, however, soon teaches those who have the practical carrying out of such works that it is well to have as little to finish off at that level as possible.

Excepting at spring tides, work so situated cannot be proceeded with at all, and should it happen that rough weather coincides with these tides, the work must wait until a more favourable opportunity presents itself—possibly a fortnight hence, but frequently very much longer.

The time occupied in the execution of work, and also its cost, are often much increased from this cause.

In bringing up work from below low water, it is best, for the reasons already stated, either to finish off the mass-work and form a level bed several feet *below* the low-water level (pp. 266 *et seq.*), and then continue the work upwards by means of blocks, or to carry the mass-work up to the level of about one-third tide.

If the latter course be adopted, it will be found that by working the tide down and up, there will be sufficient time to finish off the work and make it secure before the water reaches it, always supposing that too much is not taken in hand at one time. It may, furthermore, be worked at during neap tides as well as during springs, an advantage which, in some localities, can scarcely be overrated.

It has been stated that foundations on rock often present considerable difficulties, which, as a matter of course, are much increased when the work is situated below low water. I propose now to give a few examples.

1. *Extreme unevenness of surface.*

Here steep slopes and ridges occur, points project, and gullies and pockets are, it may be, so arranged and shaped that satisfactory work cannot be made, either with ordinary bag-work or with mass-work in frames, until some of the inequalities have been reduced.

In such cases I, from experience, strongly recommend the making of a model of the rock surface, to a scale of, say, ¼ inch to one foot. No amount of cross-sections, or soundings, or under-water examinations, can convey the same idea of the shape of the bottom, or so well enable a decision, as to how best to deal with it, to be arrived at.

Mass concrete, deposited from skips or from tripping bags (p. 267), will generally be found useful as a first step towards levelling up such foundations.

As a means of confining concrete deposited in this manner, where boarding cannot well be used, cement-bags, about three parts filled with sand, will be found serviceable.[1] These can be easily handled and built up by divers, so as to form a compact wall, which, if kept a few feet below low water, will not be disturbed even by a moderate sea.

Similar bags, filled with soft concrete, may be used in lieu of mass-work in positions where there is not room for larger bags to be deposited, and where there is no risk of their being withdrawn by the sea; but they do not form such close work as mass-concrete, and they cost more.

---

[1] The mouths of these should be sewn, not tied.

Should the site be such as to admit of mass-concrete within frames being used, this mode of construction may be resorted to after the slopes have been benched—assuming such to be necessary—and the more awkward holes and other inequalities roughly levelled up; but should the site be too exposed for this class of work, a level bed, upon which to found block-work, may be obtained either by means of bag-work (pp. 188 *et seq.*), or by mass-concrete deposited and levelled off in the manner which will be presently described (pp. 266 *et seq.*)

2. *Steeply inclined surfaces on the site of the breakwater, running either parallel to it or crossing it obliquely, as indicated in Fig.* 81.

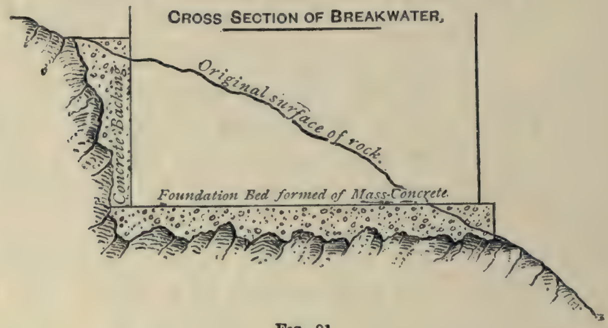

CROSS SECTION OF BREAKWATER.
Original surface of rock.
Concrete Backing
Foundation Bed formed of Mass-Concrete.

FIG. 81.

The only satisfactory way of dealing with such cases is to bench the rock, either as represented in the above sketch, or by a series of stepped benchings, as circumstances may determine. This will be facilitated by the use of *light* charges of dynamite or other suitable explosive. Heavy charges, although effecting a saving in time and labour, are likely to do mischief by shaking and breaking up the rock upon which it is intended to found the work.

3. *Steeply inclined strata, intersected by gullies, which are often partially filled by boulders, gravel, and sand.*

The danger to be guarded against here is the slipping of the rock strata[1] upon each other when loaded with the breakwater. This may be prevented either by filling the gully with concrete (after the removal of the boulders, gravel, etc., from it), by which means the ends of the strata will be supported, and slipping be rendered impossible, or by benching the rock, as represented by the dotted line *abc*, in Fig. 82. Either plan would be equally effective, so the mode of procedure should be determined, in each particular case, by expediency and relative cost.

---

[1] The joints or beds of cleavage, in granite and other igneous rocks, are often equally dangerous.

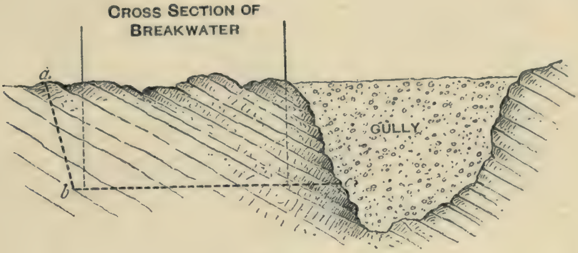


FIG. 82.

4. *Steeply inclined rock strata, crossing a breakwater and terminating by an abrupt face across the scar-end of the work.*

In a case of this kind, any attempt to bench the rock by blasting or otherwise would be almost sure to loosen it back to its natural beds, *bb*, in Fig. 83, and so make matters worse rather than better. It would, however, be out of the question to attempt to found upon such a sloping face, unless there were a substantial buttress in front of it to prevent forward slipping. Probably, therefore, the best mode of procedure in such cases is to set as much work as possible ahead of the slope, and then work backwards, closing up to the rock by means of mass concrete, as shown in Fig. 84.

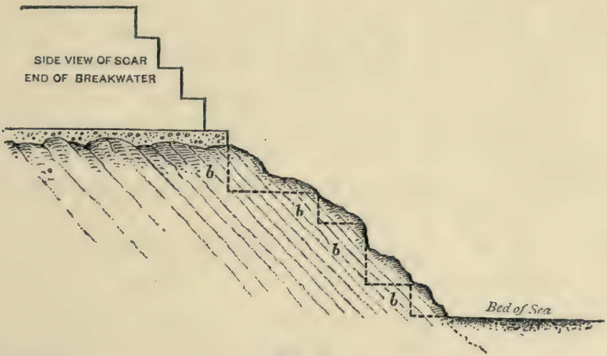


FIG. 83.

In the event of the work being constructed over-end by a setting machine which could not command a sufficient distance ahead to deal with it in this manner, the situation might prove awkward, and some other means of putting in the work would have to be devised.

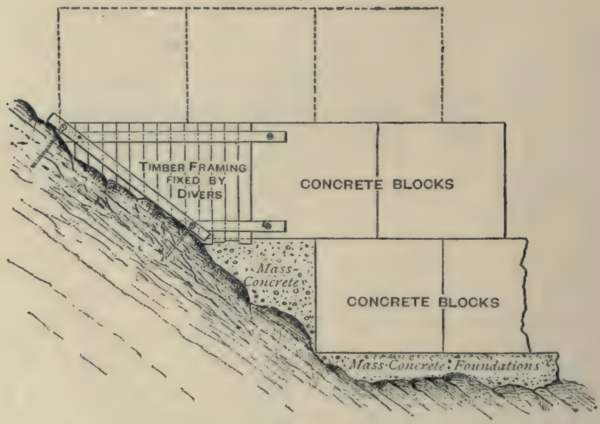


FIG. 84.

In dealing with such cases, as indeed with irregular rock foundations generally, staging possesses great advantages as compared with the over-end system of construction.

It often happens that several descriptions of work might be in progress at the same time, as, for example—

(*a*) Removing loose gravel, boulders, etc.

(*b*) Boring and blasting the rock in various positions, and removing the *débris*.

(*c*) Putting in bag-work or mass-concrete, and levelling foundations.

(*d*) Setting blocks, and so forth.

It is obvious that these several sections of the work not only might, but ought to be in progress at the same time, and this can with ease be arranged where staging is used. The case is, however, far otherwise where the over-end system is adopted, inasmuch as the setting-machine is wholly occupied when engaged on any one of the sections of work above named, its whole time being often taken up with work which could be better performed by a handy 4- or 5-ton crane or winch running upon a stage.

The advantages which staging possesses, as compared with an over-end setting-machine, in carrying on work of this kind, will thus be readily seen; nevertheless, when work is of a fairly straightforward description, the over-end system possesses many advantages, and admits of work being rapidly executed. The relative advantages and disadvantages of the several methods of constructing breakwaters were, however, discussed in the last chapter, and need not be further gone into here.

Prior to building upon rock, all sand, gravel, or mud which may have collected in pockets, gullies, or elsewhere on the line of the work, should be removed, together with all weed and other sea-growth, the rock surface being thus laid bare before the foundations are put in.

A small "grab" will often be found useful and expeditious for such work; but it sometimes happens that the site is too confined, or the rock surface too irregular, to admit of one being worked to advantage. When this is the case, the work must be performed by divers, and it becomes very costly.

When rock is soft, or of a texture which admits of its being easily worked, it is sometimes dressed and carefully levelled by divers for the reception of the foundation course, the blocks of which are laid directly upon the bed so prepared. When this system is adopted, the first course is usually treated as a compensating one, the blocks for it being made of special thicknesses, increasing by, it may be, 6 inches or a foot at a time, and the rock being dressed down to suit the nearest size.

In other cases the rock is dressed to the level which is found to entail the least amount of work, and the blocks are cut to suit it.

Where a foundation consists of hard rock, such as those of igneous origin, or of the metamorphic class, this kind of treatment is impracticable, and some levelling medium must be introduced between the irregular rock surface and the first course of blocks.

There can be little doubt that when mass-work can be put in, it makes better and closer work than bags, because, however well the latter may be packed, they cannot make homogeneous work, neither can a sufficiently true bed be formed by them to found blocks upon without their surfaces being trimmed off or levelled in some other way.

Until recently, however, bags of concrete were commonly used for founding blocks upon, the formation of accurately levelled beds of mass-concrete under water not being considered practicable.

In view of the advantages which would accrue if some means of doing such work could be discovered, I gave the subject very careful attention, and succeeded in devising a plan which has proved quite satisfactory in practice. It has already been referred to, but I will now describe it at greater length, and, in doing so, will quote from an account of it which was given in *Engineering* of September 16, 1892.

"The method may be thus described: Let *ab*. Fig. 85, represent the level at which it is required to found the lowermost course of blocks, at any convenient depth below low water. Careful longitudinal sections are taken along the lines of the inner and outer faces of the foundation, as at *c*, or, if it should be a wide one, upon intermediate lines also, and these are plotted, full size, upon a floor. Planks are then cut and made up by nailing on boarding, where required, to correspond with the irregularities of the bottom, as represented in Fig. 86. These are weighted with iron to the extent necessary to make them sink, and they are fixed by means of bolts, from 2 feet to 3 feet in length, let into the rock, as shown, and secured by iron wedges. Wedges are used in preference to making the bolts in the form of lewises, in order that they may the more easily be withdrawn for use in the succeeding lengths of foundation.

FIG. 85. CROSS SECTION.

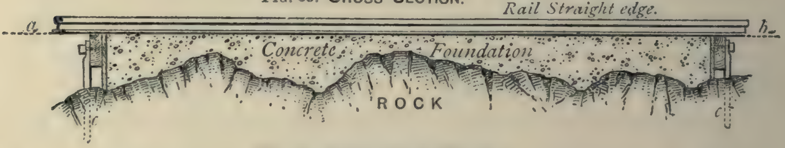
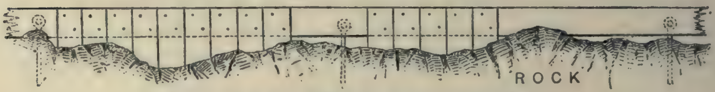


FIG. 86. ELEVATION OF PLANK SHOWING BOARDING &C.



Mass-concrete foundation for under-water work.

"The planks are fixed by divers, and in moderate depths their level is determined by means of an ordinary field-level and staff, the latter being provided, if necessary, with a 10-feet or 15-feet lengthening piece. A diver holds the foot of the staff upon the top of the plank, which is raised or lowered according to signal. It is thus fixed at its correct level with perfect ease and accuracy. If found to be more convenient, the divers may themselves adjust the plank by means of an ordinary spirit-level. This having been done, coach-screws are inserted through the eyed ends of the bolts, for the purpose of holding the planks in place.

"Before lowering the planks for fixing, the surfaces which will be in contact with the concrete are covered with jute sacking, a flap of the same material, from 15 to 18 inches wide, being left so as to extend under the concrete and prevent its escape. A length of about 20 feet of foundation is usually dealt with at one time; but this, of course, is merely a matter of convenience, which may be regulated as circumstances require.

"Where the mass of concrete required to level up a foundation is large, it may be composed of, say, 4 or 4½ parts of good clean sand and gravel to 1 part of Portland cement, the top being finished off with a layer, about 6 inches in thickness, of rich concrete composed of 2 parts of fine gravel and sand to 1 part of Portland cement. Where the thickness of the concrete is small, only the richer compound should be used.

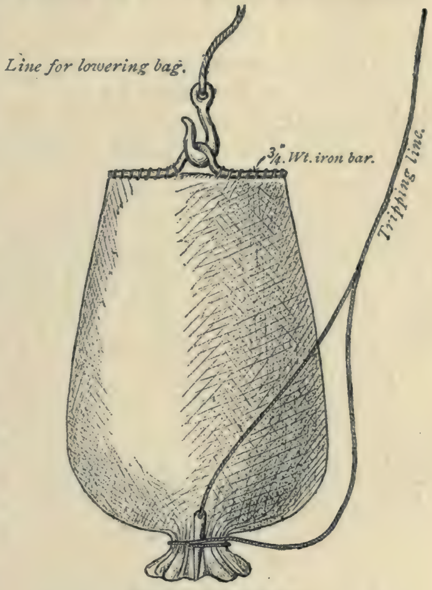


FIG. 87.—Tripping bag.

"The concrete is lowered to the divers in bags specially designed by Mr. Shield for the purpose. These are illustrated by Fig. 87. The mouth of the bag is closed by *one* turn of a line which is provided with loops through which a hard wood tapered pin passes. This is attached to the tripping line, as shown in the engraving. The folds of the bag hold the pin in position, but a slight pull is sufficient to withdraw it and release the contents of the bag. The bags are made slightly tapered, say 3 inches on a side, so as to facilitate the discharge of the concrete. They should be lowered, mouth downwards, until they almost touch the bottom. The divers then place them over the site where the concrete is required, and on giving the signal 'All right,' the tripping pin is withdrawn and the contents of the bag deposited.

"The loss of cement by this system is so small that the water is scarcely discoloured. The bags usually contain 2¼ cubic feet each, but bags of any convenient size may be adopted. A straight-edge (a light section Vignole's rail makes a good one) rests upon the upper edges of the side planks, and spans the distance between them.

"The divers commence the foundation at one end, and work backwards, so as not to disturb the newly deposited concrete. The concrete is merely pressed down by the flat hand to the required level, and gently struck off by the straight-edge. In this way a perfect surface is formed, which, at a depth of 5 feet or 6 feet below low water, is undisturbed by small waves.

"In the course of a few hours the concrete becomes sufficiently hard to resist a moderate sea, and after three days it is hard enough to bed blocks upon.

"It is considered essential to success that the concrete used in forming foundations as described should be thoroughly well mixed, enough water being used to form it into a not too stiff slimy paste, which should be put into place as soon after mixing as possible.

"The system is applicable to the levelling of bag-work or rubble foundations, as well as rock; but in the case of rubble foundations, it is necessary to cover the entire area with jute sacking, in order to prevent the concrete finding its way down amongst the stones."

Concrete mass-work within frames, also bag-work, have already been described (pp. 183 *et seq.*), so, although largely used in foundation work, they need not be further noticed here.

Where a rock bottom is fairly level, small irregularities are sometimes adjusted by means of a layer of broken stone similar to road metal. In order to prevent its escape, small bags of soft concrete are sometimes placed along the margins of it, as shown in Fig. 88. These should be placed immediately before the setting of the blocks, in order that the blocks may, by their weight, bed themselves well down upon the metal, and squeeze the concrete in the bags down to the level required. The concrete in these bags should be extra good, and free from large stones.

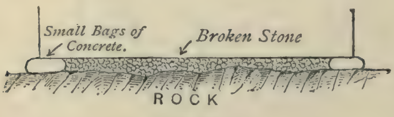


Fig. 88.

After blocks have been so bedded, the broken stone should, if possible, be grouted with neat Portland cement grout, or with grout composed of Portland and Medina cements in equal proportions, introduced through the lewis-holes, or through holes specially made for the purpose, by means of pipes extending to above the water-level. The pipes should be carried well up, in order that the "head" so obtained may force the grout amongst the stones and out to the margin. By this means, if due care be taken, a secure foundation may be formed; but it is evident that, in the event of the broken stone not being satisfactorily grouted, the very existence of the breakwater would depend upon the marginal bags remaining undisturbed.

In theory the system has the appearance of being a good one; but in practice it is found that, if the ground should be at all uneven, it is exceedingly difficult for divers to place the bags sufficiently level and regular to ensure the superposed blocks compressing them all equally. It is, further, not possible to provide against the concrete in the bags, after having been squeezed—even assuming that none of the bags have been burst in the process—falling away from the blocks to a small extent. The blocks cannot follow such shrinkage, on account of their being hard bedded on the broken stone; so, when once the bags have become slack—$\frac{1}{8}$ inch settlement would suffice to free them—they are liable to be withdrawn by the sea, in which case the broken stone would soon follow, thus causing voids, and endangering the stability of the work.

The foundation of the landward portion of the Hermitage breakwater at St. Heliers, Jersey, was formed in this manner, and it did not prove satisfactory. In reporting upon it, Mr. Kinipple stated—

> "From the foundation area, many of the smaller bags, the whole of the broken stone, and some of the rubble and concrete filling between, had been washed out by the action of the sea, leaving cavities, in some cases, large enough to admit of a diver getting underneath the foundation course of blocks" (*Engineering*, vol. liii. p. 647).

When the bed of broken stone can be placed at a sufficient depth below low water, and secured by means of an efficient apron, it forms a useful and ready means of preparing the bed for the foundation course, and it is much used in founding blockwork upon rubble mounds; but under other conditions it cannot be considered a safe mode of construction, unless the broken stone be effectually grouted, as just described.[1]

---

[1] The system of passing cement grout through water for such purposes as the stoppage of leaks in lock sills, etc., has been known and practised for a number of

Department of Civil Engineering
Municipal and Structural

Where the depth of water and other conditions are such as to admit of inequalities of rock being made up by the deposit of rubble, the same methods of founding blocks may be adopted as in the case of work founded upon a rubble mound, which we will shortly consider. I would, however, here draw attention to a danger which attends the levelling of rock inequalities with rubble. I refer to unequal settlement arising from unyielding peaks of rock approaching too near to the surface of the rubble. This cannot be too carefully guarded against. The Manora breakwater at Kurrachee sustained serious damage from this cause.[1]

Founding upon Sand.—Sand, being practically incompressible, forms an excellent foundation, *so long as it is not allowed to escape.* When, however, a rubble mound breakwater, or one composed of blocks thrown in pell-mell, is placed upon a sandy bottom, the rubble or blocks, as the case may be, will soon subside to a certain extent, owing to the wash of the water about them excavating the sand and drawing it away. They thus gradually settle down, find their bearing, and become stable.

In placing a vertical breakwater upon a sand foundation, it is necessary, in the first instance, to protect the sand from scour. This is usually done by depositing a thick layer of rubble stone over the site to be occupied by the breakwater, and extending it well to seaward, so as to form a wide apron. It should also be extended—though not necessarily so far—on the sheltered side, this being requisite, not only for the purpose of checking scour set up by currents and wave-action during construction, but also for protecting the sand from the excavating action of water thrown over the pier during storms.

If the site is much exposed, this apron may itself require protection along the seaward face of the breakwater as the work progresses, and this may readily be given either by depositing blocks or large bags of concrete.

At Ymuiden, where the breakwaters are of the vertical type, and founded upon sand, the covering layer of rubble is, for the most part, about 3 feet 6 inches thick; but in some places it is

---

years. Attention has, however, recently been directed by Mr. W. R. Kinipple, M. Inst. C.E., to its value when applied to breakwater construction, especially to the grouting of rubble in foundations, etc.; and he has done good service by developing the system and bringing it into more general use.

[1] *Min. Proc. Inst. C.E.*, vol. xliii. pl. ii.

considerably thicker. It extends on either side of the piers for a distance of about 50 feet, and on the seaward side it is protected, near the bases of the piers, by wave-breakers of concrete blocks, which also give additional stability to the piers themselves.

When scour took place along the edge of the rubble, as was invariably the case soon after it was deposited, the rubble subsided as the scour progressed, and formed a rough rubble slope, which effectually encased and protected the sand underlying the piers.

At Tynemouth, where the breakwaters are also of the vertical type and founded upon sand, the same system was adopted. The rubble was, however, deposited over a greater width than at Ymuiden, and the blocks, weighing 36 tons each, which were deposited along the seaward faces of the breakwaters, merely formed aprons, as they were not carried up high enough to constitute wave-breakers.

With the object of avoiding or reducing the excavating action of waves playing against a vertical face, some engineers favour a curved profile for breakwaters, such profile being either the arc of a circle, a cycloidal curve, or, indeed, almost any other which fancy may suggest. It has, however, been found in practice that all such curved profiles throw the water higher than a straight, vertical face, and that they rather increase than diminish the scour at the toe of the wall, notwithstanding that they may meet the beach-line almost tangentially. They are, moreover, very difficult to construct under water, and they are weak structurally, presenting, as it were, the intrados of an arch to the wave-stroke. In cases where walls with curved profiles have been built, it has generally been found necessary to protect their toes by throwing down large rubble stones, unless they happen to have been founded upon rock.

Sometimes, when sand overlies more stable ground, it is removed by means of a sand-pump, or in some other convenient way, the breakwater being founded upon the firmer bed thus laid bare. In some instances caissons have been sunk, and the work built inside of them.

Mud contrasts unfavourably with sand, because of its extreme readiness to yield when weight is applied. Hence the systems of dealing with sand foundations, as just described, are not always applicable to a mud bottom.

The covering of rubble would sink into the mud in much the same way as into sand, but it would yield and continue to sink as more weight was placed upon it.

When mud is not of great thickness, it is well, as in the case of sand, to remove it, and found upon the more solid ground underneath, unless one or other of the types of mound breakwaters be adopted, in which case any settlement which might take place could be easily made up.

Should a vertical breakwater, however, be a *sine quâ non*, and a sufficiently solid base to found it upon be unobtainable without having recourse to artificial means, the necessary amount of stability may be obtained, if the depth of water be not too great, by driving timber piles—say 12 or 13 inches square—about 4 feet apart, centre and centre, over the entire area to be occupied by the breakwater. The heads of these should be cut off perfectly level, and well below the surface of the mud, so as to ensure them against attack by sea-worms. Sills should then be halved into the piles and bolted to them, so as to connect them together and afford support to close 6-inch planking, which should be spiked to the sills so as to form a platform whereon to build the superstructure. Sometimes two layers of planking are laid crossing each other at right angles, and sometimes planking is omitted altogether. In the latter case, the mud is removed for a depth of 4 or 5 feet below the pile-heads, and rich mass concrete is put in.

The construction of a breakwater upon such a foundation, either by means of blocks or concrete in mass, is then a tolerably straightforward piece of work.

In a work of this kind, wide and substantial aprons must be provided, to secure it from injury by scour and undermining. Should such take place, or should the worms be allowed access to the timber, the stability of the work would be endangered; but if the timber-work be kept well down and always buried, no anxiety need be felt in regard to its endurance, as it will be practically imperishable. A row of sheet piling along each side of the foundation will add much to its security.

There are other methods of dealing with a mud bottom, as, for example, by sinking caissons, as before referred to, or by dredging a trench, either between rows of sheet piling, or of sufficient width to allow for side slopes, until a firm bottom is reached, and then depositing rubble or concrete.

In some cases the difficulties of a mud bottom may be best overcome by adopting the timber-framed type of breakwater.

Gravel requires much the same treatment as sand.

Clays must be dealt with according to their character, some being almost as soft and treacherous as mud, while others are sufficiently hard and compact to found directly upon. In all cases, however, protection from scour should be kept prominently in view.

Sufficient has now been said to indicate the general principles upon which foundations on the several kinds of natural ground should be treated, so we will devote the remainder of this chapter to describing the founding of breakwater superstructures upon rubble mounds.

Founding upon Rubble.—During the time that a mound upon which it is intended to erect a superstructure is being deposited, and especially as it approaches the level at which the superstructure will be founded, accurate soundings should be taken at close intervals, in order to prevent the rubble being carried up too high.

In the last chapter, it was mentioned that the surface of a mound, say the last 2 or 3 feet, is best formed by stones of moderate size thrown by hand from boats or barges, to the extent which soundings may show to be necessary.

Almost the whole of the rubble forming the bases of the Ymuiden and Mormugão breakwaters was deposited in this way, it having been found cheaper and more satisfactory than using hopper-barges. The same system was adopted for roughly levelling the surface of the mound at Colombo.

The usual method of levelling up inequalities, and forming a true bed for the reception of blocks, whether these are to be laid in horizontal courses or on the sloping system, is, after having roughly levelled the rubble, to deposit a layer of small broken stone or masons' chippings, which the divers pack and arrange to the level required. If this is carefully done, it forms a very good bed for the first course of blocks to rest upon.

The small stone should be confined, as soon as possible after the placing of the blocks upon it, by depositing additional rubble along both faces of the breakwater, and, if necessary, temporarily across the scar-end also, the marginal bags of concrete illustrated on p. 268 being dispensed with.

When a mound is not sufficiently compact to warrant a levelling of small stone being placed directly upon it, the surface may first be covered, and thus sealed, by a layer of soft concrete in small bags; or the rubble, after having been roughly levelled, may be covered with canvas, and a bed of mass concrete deposited, as described on pp. 266 *et seq.*

When a mound has been formed by depositing stone of all sizes in due proportions, it is practically impermeable, and in such cases a levelling of small broken stone and chippings is probably the readiest means of forming a true bed; but when only selected stone, to the exclusion of small, has been used, about one-third of the mound consists of voids, and there is necessarily a rush of water through it as each wave rises against the face of the superstructure.

In a mound thus formed, a levelling bed of small stone, unless secured as above described, or in some other efficient way, would be almost certain to work down into the voids of the mound, to the manifest injury of the work. Other precautions, necessary in using small stone for foundation work, were noticed when we were considering rock foundations (pp. 268 *et seq.*).

CHAPTER XVI.

SETTLEMENT AND BOND.

Settlement can seldom be altogether avoided—Usually greatest in breakwaters of mound type—Increased by weight of superstructure—Unequal settlement—Weight of heavy setting-machines injurious to new work—Settlement of breakwaters at Holyhead, Alderney, Colombo, Mormugão, and Manora (Kurrachee)—Bond—Objections to—Vertical bond—Evils attending "dry bedding" of blocks—Objections to "stretchers"—Dowels—Notching—Tabling—Dovetailing—Absence of bond in Manora breakwater—Sloping coursed work accommodates itself to settlement—Bond of blockwork in Tynemouth breakwaters.

Settlement.—Excepting in the case of breakwaters built upon a rock foundation, more or less settlement can seldom be avoided. It is usually greatest in those breakwaters which are composed, either wholly or in part, of rubble mounds, seeing that in them it is produced not only by the yielding of the ground upon which they stand, but also by the consolidation and shrinkage of the mound itself. When a mound rests upon an unyielding bed, settlement still takes place, but, as a matter of course, it is then due to the latter cause only.

In constructing composite breakwaters with rubble mound bases, if sufficient time be allowed to elapse between the deposit of the rubble and the building of the superstructure upon it, the mound will, in a measure, be consolidated by wave-action, and will still further gain stability by collecting sand and other drift material. Experience, however, shows that, no matter how long a mound may have been exposed to these consolidating influences, the application of weight almost invariably causes further settlement to take place. It therefore follows that, however stable a mound may have apparently become, further subsidence is sure to take place when it is called upon to support the weight of a superstructure.

Moreover, when a rubble mound is stopped at the level of, say, 20 feet or more below low water, it will be very little affected, even by the heaviest seas, until the superstructure has been placed upon it (p. 201).

Seeing, therefore, that settlement cannot be avoided, our aim should be to ensure its being as uniform as possible. In this respect staging offers facilities which do not pertain to the system of over-end setting.

By the former method the work can be gradually raised over a considerable length of foundation, which is thus more evenly loaded than is possible where over-end setting is resorted to, and it is further relieved from the weight of the setting-machine, which in some of the more modern examples is excessive, and such as to prejudicially affect new work founded upon a yielding foundation, such as we are now considering.

When unequal settlement occurs, the superstructure is often fissured, blocks are loosened, and the lower courses not unfrequently fall away from those overlying them, in which case serious damage ensues, as has already been pointed out (pp. 181 *et seq.*).

Breakwaters built with sloping courses readily accommodate themselves to settlement by an exceedingly small opening of the joints, which we will further consider when speaking of bond (p. 283).

General uniform settlement is of comparatively little importance. A settlement of about 3 feet 6 inches—approximately $\frac{1}{15}$ the height of the mound—took place in the Holyhead breakwater after the superstructure had been built, but the movement was so gradual and regular that the work was not affected by it.

At Alderney the settlement amounted to about $\frac{1}{20}$ the height of the mound, or to a maximum of about 6 feet. This cracked the superstructure, and otherwise injured the work. The mound of this breakwater was, however, of exceptional height, and the superstructure was particularly liable to produce unequal settlement, owing not only to its design, but also to the manner in which it was built.

With respect to this, Mr. Vernon-Harcourt, M. Inst. C.E., states—

> "As, however, it was very important to raise a certain length to the level of low water each fortnight during the working season, so that the masons might commence on the cemented courses as low as

possible at each spring tide, and also in order that the blocks under water might be secured by the weight of the masonry on them, it has been customary to found the superstructure in suitable lengths, leaving a break at the close of each fortnight's work; and each season's work was terminated by a carefully protected scar. Accordingly, the superstructure was composed of a series of lengths, formed at different periods, between which unequal settlement of the base necessarily occurred; and a still more marked division was formed at the close of each season's work. The junctions formed so many weak points in the superstructure, where serious disruptions tended more or less to occur. Above low water these cracks could be filled up, unless extending far into the interior of the superstructure; but below low water no means could be used for filling up the crevices, and the waves, rushing in, caused a compression of the air inside them. This resulted in the forcing out of face-stones about low-water mark, which were also liable to drop a little, owing to the lowering of the base."[1]

In the Colombo breakwater, where the superstructure is composed of sloping blocks, the settlement amounted to about $\frac{1}{10}$ the height of the mound, measured from the sea-bed to the base of the superstructure; nevertheless, the superstructure followed it down, as at Holyhead, without any appreciable disturbance of the work.

The settlement in Mormugão breakwater, owing to the bottom being of mud, was somewhat greater than at Colombo, being about $\frac{1}{8}$ the height of the mound; but in this case also the sloping blockwork followed it down without sustaining any injury.

The Manora breakwater, also of sloping blocks, settled to the extent of about 3 feet over the greater part of its length; but in some places, owing to peaks of rock protruding, the settlement was irregular, and the work in this instance was damaged.

In order to compensate for settlement, when the sloping block system is adopted, an estimate of its probable amount may be made, and each successive length of the work may be kept correspondingly high. In horizontally coursed work, however, settlement in sections is much more difficult to deal with, and, as will be readily understood, it is likely to be productive of much mischief.

When a breakwater composed of a rubble mound and vertical superstructure is projected from a steep rocky shore, difficulty is often experienced at and near the point where the mound meets the rock. At this point unequal settlement frequently takes place to such an extent as to badly crack the work. This may, to some extent, be met by forming a vertical joint at that point, right across and from top to bottom of the superstructure, the object being to localize, as far as possible, the disturbance caused by the settlement. When settlement has ceased, the joint may be filled up and made good by grouting.

---

[1] Harcourt, "Harbours and Docks," p. 114.

Bond in breakwaters and in works of a like kind differs from that in most other structures, inasmuch as it is seldom required to distribute weight, or to tie the work together longitudinally. Indeed, it is sometimes contended that bond of any kind in a breakwater is an evil, seeing that it tends to prevent the structure from freely accommodating itself to settlement, in the event of such taking place.

In arranging the bond of a sea-work, vertical movement may, however, be provided for, and it should, no doubt, be kept prominently in view, while at the same time the withdrawal of any individual block should be rendered as difficult as possible.

A breakwater composed of large monolithic blocks, of the full width of the structure, bonded to each other by vertical grooves and tongues, as in Fig. 89, would, so far as bond is concerned, be an ideal one; but in practice such a mode of construction is not always possible or expedient.

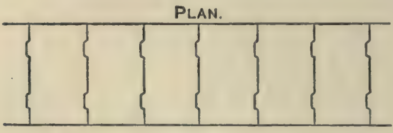


FIG. 89.

Attention has already been directed (pp. 181, 182, 244) to the mischief which may result from the "dry bedding" of large blocks laid in horizontal courses, but it may not be out of place to again refer to the subject here.

It was pointed out that when blocks are merely laid one upon another in horizontal courses, without any bed of cement between them, unless the surfaces are perfectly true, and the blocks laid in exactly the same plane, they cannot bear evenly upon each other. Hence, as the weight of superposed blocks is applied, those underneath are subjected to transverse strains; and if these should be intensified by leverage, as would be the case if long longitudinal bonding-blocks or "stretchers" were introduced, the blocks, which possess practically no elasticity, would in all probability be broken.

Even in a blockyard, when blocks are stacked too high, or without due care, the lowermost of them are sometimes fractured; and I have known ashlars of Bramley Fall stone to be broken in the same way. Long blocks are, moreover, liable to "bridge" local settlements, and thus allow the blocks below them to become loose and fall away.

From what has been said, it will be seen that all blocks should be laid as "headers," alternate face-blocks being made shorter than the others, so as to give such transverse bond as may be deemed necessary.

FIG. 90. [ELEVATION]

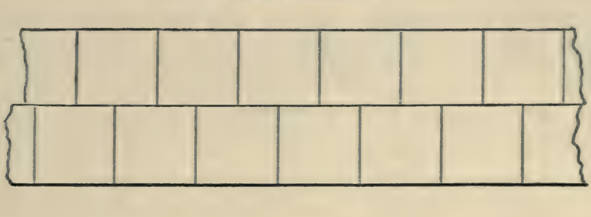
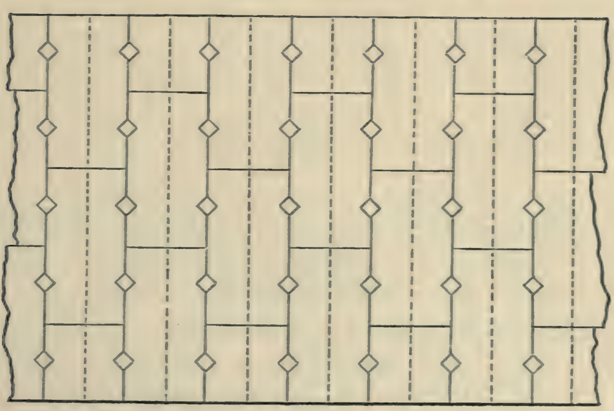


FIG. 91. [PLAN]



The bond ordinarily adopted in breakwaters for horizontal coursed work is shown in Figs. 90 and 91.

Various expedients have been resorted to in order to prevent the withdrawal of individual blocks, but ordinary dowelling or joggling (Fig. 91) is perhaps as simple and effective as any.

Joggles are usually made of fine, rich Portland cement concrete, though sometimes of slate or other suitable stone. They ought to be somewhat smaller than the holes they are intended to occupy; and after having been deposited in the holes, they should be well grouted.

An efficient method of forming joggles in under-water work is to place a canvas bag in the joggle hole, and fill it with fine Portland cement concrete (say 3 parts of fine gravel to 1 of cement).[1] The bag should have a properly shaped flat bottom, and it should be slightly larger than the hole.

An elongated tripping bag will be found a convenient means of lowering the concrete through the water and depositing it.

When under-water grouting is resorted to, ordinary joggles, formed so as to allow of the grout passing around them, may be inserted in the holes before grouting commences. If, however, the joggle holes are small, the grout alone will suffice to fill them.

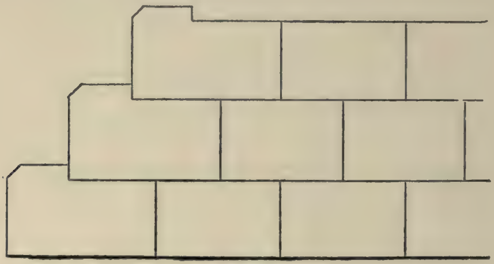


FIG. 92.

Sometimes small bags of concrete are rammed into the holes; but these do not make such close or satisfactory work as the methods above described. Loose joggles, if exposed to wave-action through open joints, may become a source of danger to work.

In fissures amongst rocks it is common to find cavities which have been formed and gradually enlarged by the rolling about of boulders within them. A boulder—probably thrown into a fissure by the waves—becomes lodged in some place from which it cannot escape, and by constant movement, due to the waves, it erodes the rock, and so forms a cavity, which, as it enlarges and the boulder gains more freedom, becomes a veritable mill.

In the same way a loose joggle may enlarge the hole which it occupies, and by degrees be itself completely worn away, the eroded material being withdrawn by the play of the waves into the open joints. The danger of such cavities in work has already been frequently referred to.

---

[1] For small joggles, say up to 3 inches square, cement mortar, composed of equal proportions of Portland cement and sand, thoroughly well mixed, so as to form a thin slimy paste, is preferable to fine concrete.

In some cases the face-blocks of battered work have been secured in the manner indicated by Fig. 92. This system is suitable for the stepped facing of blocks sometimes used for protecting the slopes of rubble mounds, but its success depends to a very great extent upon the care with which the bottom blocks are laid and secured.

Fig. 93. [Section]

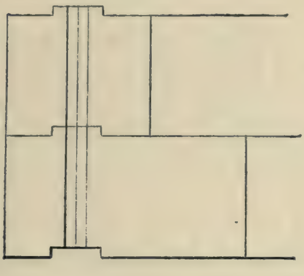


Fig. 95. [Plan]

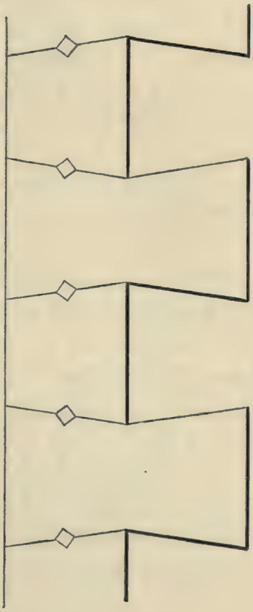
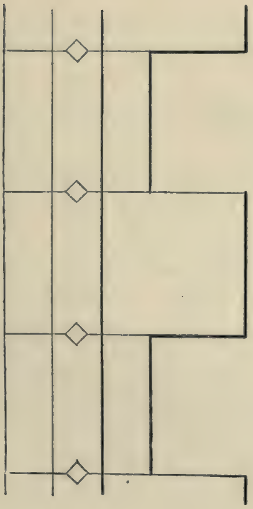


Fig 94. [Plan]



Figs. 93 and 94, p. 281, show a system of "tabling" often used in lighthouse work. It is suitable either for straight or for round work, and may be advantageously used in pier-heads in exposed positions. The face-stones in several of the courses in the head of Alderney breakwater were notched or "tabled" in this manner, others being merely dowelled, as in Fig. 91, p. 279.

Dovetailed work (Fig. 95, p. 281) is essentially a lighthouse form of construction. It is seldom used in breakwaters, unless under exceptional conditions, but it was adopted for the ashlar work at the toe of the sea-slope of Plymouth breakwater, where much trouble was experienced in getting any work to stand.

Any of these fancy-shaped blocks, if cut in stone, are very expensive, but if moulded in concrete, very little extra cost is incurred.

With the view of allowing the sloping block-work superstructure of the Manora breakwater perfect freedom to settle the blocks were laid without any bond, and the breakwater was divided from end to end, and from top to bottom, by a vertical central joint. In fact, it was composed of two vertical walls, each about 24 feet in height, and 12 feet in thickness, touching each other, but not connected in any way, the blocks in each wall being placed one upon the other, like so many slightly inclined basaltic columns.

The walls moved and settled independently, as was intended, but they did so to a greater extent than was anticipated, with the result that the central joint opened in some places to a considerable extent, and a number of blocks in both walls, but chiefly in the one on the harbour side, were displaced by the sea.

It is frequently and rightly claimed as one of the advantages pertaining to sloping block-work, that the courses are free to slide upon each other, and thus to follow any settlement which may take place. This is more particularly the case during construction, when the end of the work is comparatively free, and when local settlement is specially liable to occur.

In a properly constructed work, the pressure exerted by the tilted courses leaning against each other, coupled with the dowelling which is almost invariably introduced, should, when the work is finished, be sufficient to prevent this sliding motion; but in the event of settlement taking place, the joints, being the weakest points, would open to the necessary extent, and allow the work to follow it down.

Thus a settlement, even to the extent of 3 feet, occurring at any point, and gradually dying away on either side of it in a distance of, say, 200 feet, would be met by the opening of each joint, assuming there to be 100 of them, to the extent of less than $\frac{1}{130}$ of an inch, or little more than what is termed a "hair-crack."

A good bond for sloping block-work is that which was adopted for the Colombo breakwater (Fig. 38, p. 195).

In that work, the blocks forming each tier, or tilted course, "broke bond" to the extent of about 5 feet, and the tiers were further bonded together by means of vertical grooves 18 inches wide, which, coming opposite to each other, formed continuous holes from the top to the bottom of the work. These were filled with strong soft concrete in bags, well rammed in, which, when hard, performed the part of dowels or joggles. There were five such continuous dowels in each tier of blocks, and they were placed about 6 feet 6 inches apart.

In order to prevent blocks sliding upon each other in horizontally coursed work, horizontal dowels may be introduced, or short pieces of bar steel or iron,"[1] may be placed vertically half in each course, and grouted either through a hole provided for the purpose, or through the lewis-holes in the blocks, as may be most convenient.

Instead of introducing pieces of rail, recesses may be formed in the blocks immediately underneath the lewis-holes, which, when grouted, will form cement dowels. The introduction of short pieces of rail or iron dowels, however, adds greatly to the strength of any such arrangement.

In the Tyne breakwaters, Mr. P. J. Messent, M. Inst. C.E., with the object of preventing the sliding of one course upon another when struck by a heavy sea, introduced what he called "piano blocks." This system of bond is illustrated in Fig. 96, the "piano blocks" being indicated by shading.

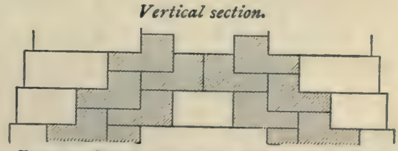


FIG. 96.—Sketch showing bond of blocks in Tyne breakwaters.

In addition to the several kinds of bond already described, iron cramps and bolts are frequently used for tying work together.

---

[1] Old permanent-way rails do very well.

CHAPTER XVII.

SILTING.

Process described—Wave and current action—Effect of piers projected from the shore—Advance of foreshore—Prolongation of jetties—Dredging—Sluicing—Harbours on sandy coasts—Outlying isolated breakwaters—Direction of drift.

SILTING is the term commonly used to denote the deposit of matter which is held in suspension by sea-water in proximity to the shore, or the accumulation of that which is made to travel along the sea-bed by the action of waves and currents.

The process of silting may be described as follows: the waves, together with the tidal or other currents, erode the sea-bed, and also the shores and cliffs along the coast. The material resulting from this erosion is separated and sorted by wave and current action, the larger and heavier particles settling down and being rolled along the bottom, while the smaller and lighter particles are held in suspension by the water.

These latter depend entirely upon the motion of the water for their support; so when silt-laden water enters a close harbour, or other becalmed area, and the disturbing influences cease or are much reduced, the particles forthwith settle to the bottom by reason of their gravity.

In the more sheltered parts of a harbour, the agitation of the water is not generally sufficient to stir up this deposit when once it has settled down, so, when the water ebbs away, the material which came in with the flood tide is left behind.

This process is repeated each tide, and unless means be adopted for removing the material so deposited, the harbour gradually becomes shallower, and is ultimately choked and rendered useless.

Whilst the waves are keeping the water in a state of agitation, and thus assisting the currents in transporting the fine material with which they are charged, they still further help to fill up harbours by rolling sand and shingle along the sea-bed, and driving them into the harbour entrances. They also heap up drift materials against obstacles, such as piers, etc., which run across the shore along which the drift travels; but when such piers extend into deep water, a considerable time often elapses before the drift material—as distinguished from that held in suspension—finds its way into the harbour, because the corners which the piers form with the coast, constitute traps for it. As, however, these fill up, an advance of foreshore takes place, and the material finds its way out to and round the pier-heads. Should these occupy a salient position, and extend well into the tide-way, the current past them will scour much of this away, and enable the depth of water at the entrance to be more easily maintained than under other conditions. Nevertheless, a current in passing an entrance often expands into the harbour and creates eddies, by means of which some of the drift material is almost sure to be carried in, and deposited under the lee of the piers. Total immunity from dredging can therefore scarcely be expected.

In order to combat the advance of foreshores, jetties are often extended seaward; but such prolongations, unaided by dredging, are generally found to be of little permanent benefit, inasmuch as each extension of the pier causes a corresponding advance of the shore. The rate of such advance depends upon the physical conditions peculiar to each site, and especially upon the quantity of sand in motion. This varies greatly in different localities—hence, while the extensions of the jetties at such ports as Calais and Dunkirk have failed to produce the desired results, the prolongation of those at Port Said has been more successful; so much so, indeed, that it has been estimated it will take three centuries for the foreshore at Port Said to advance to the end of the piers, assuming its present rate of accumulation to be maintained.[1]

In order to keep open the Ymuiden harbour, it has been found necessary to dredge, on an average, about 650,000 cubic yards of sand per annum, at an average cost of about £22,000.

Such an expenditure as this can only be met by a very large traffic, and there can be little doubt that but for this Ymuiden harbour would ere now have ranked amongst the failures of harbours on sandy coasts. In view, however, of the very large amount of traffic which passes through the Amsterdam ship canal, at the west end of which Ymuiden harbour is situated, and of the success of the whole undertaking, it is evident that those who planned the work were fully justified in the view they took.

---

[1] *Min. Proc. Inst. C.E.*, vol. lv.

And here it may be remarked how largely the success or failure of a work is affected by the factor of revenue. A harbour similar in all respects to that at Ymuiden, but lacking its large revenue, would prove an absolute failure. The same may be said of many other harbours around our own coasts and elsewhere, where the amount of dredging required to keep them open is very great.

The value of tidal and upland waters for scouring away and preventing accumulations of silt, also the evils resulting from a reduction of the volume of tidal water, by reclamations or otherwise, have already been dwelt upon (Chap. IX.).

In order to increase the scouring power of the ebb tide, large quantities of water are sometimes impounded at high water, and released by means of sluices during the latter part of the ebb. The effect of such sluicing is not, however, generally felt beyond the pier-heads; and in long channels, where the entrance is far removed from the sluices, the power of the water is often lost long before the harbour entrance is reached.

The construction of harbours on sandy coasts is admitted to be a difficult problem, and in many instances it would doubtless be better to avoid, than attempt to overcome, the difficulties arising from sand-travel. This can probably best be done by placing the sheltering breakwater in deep water beyond the field of sand-travel.

If, in addition to affording shelter, it should be intended to use such a breakwater as a quay, it might be connected with the shore by means of an open viaduct. In such a work quay-room could, if necessary, be increased by running out jetties shorewards under lee of the breakwater, or the ends of the breakwater might be returned so as to form a basin.

Works designed on this principle were proposed for the port of Calais by M. Dupuy de Lome and Mr. Scott Russell; also for Madras by Sir Andrew Clarke, R.E.; and subsequently for Port Elizabeth, Cape Colony, by Sir John Coode; but in no case was effect given to these proposals.

It is not necessary that a harbour should be what is termed a "close harbour" to encourage silting, inasmuch as the becalmed area under the lee either of a single breakwater projected from the shore, or of an isolated one within the zone of sand-travel—even though it be approximately parallel to the coast—is often quite as effective in causing deposit to take place. In the latter case—the shore being sheltered from the waves, which undoubtedly play the principal part in the travel of sand and other material along a coast—there is, in the absence of a sufficiently strong current, no power by which the sand can be passed on when once it has reached the becalmed area; the inevitable result being the formation of shoals.

A good example of this action is to be found in the familiar spit of sand or shingle which so often connects outlying rocks with the shore, as represented by Fig. 97.

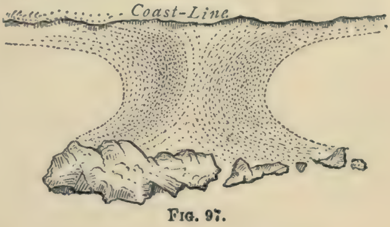


FIG. 97.

Where littoral currents exist, they may, in a more or less perfect manner, according to their strength, counteract the power which the waves exert in causing sand to gather in such positions; but littoral currents are often as fickle as the weather, and require very careful study before reliance can be placed upon them.

It would, therefore, in many cases be dangerous to place a work of magnitude so close to the shore as to shelter it, and it follows that the larger the proposed work the further ought it to be placed from the shore.

One has not far to look for examples of harbours which have become useless, or dependent upon dredging to an unnecessary extent, by reason of littoral drift having been insufficiently considered, or not properly understood, at the time the designs for them were framed.

The direct part which wind plays in causing sand to travel along a coast has already been referred to (pp. 20 *et seq.*).

Before works are undertaken upon a shore where sand or shingle travels, the physical conditions of the site should be very carefully studied. The investigation should embrace the coast for a long distance on either side of the site of the proposed work, and if the natural form or condition of any point of the coast should be such as to admit of comparison with the proposed work, or of useful deductions being drawn therefrom, such should be carefully noted.

The relative strength and duration of the flood, ebb, or other littoral currents, considered in relation to the wave-action on the shore, will indicate the preponderance of scouring power in one direction or the other, and so the probable direction of drift; but every effort should be made to substantiate, or otherwise, any theory based upon such observations by others of a more direct nature.

For such purpose small coal, pieces of burnt clay, or other easily recognizable material, may be deposited at points along the coast in various depths of water, and its movement be noted, it being remembered that the direction of drift may vary with the weather or season.

INDEX.

A

Aberdeen, cost and other particulars of south pier, 219
——, damage to south pier, 182
——, early use of sloping blocks at, 197
——, large bags of concrete first used at, 189
Advance of foreshores, 285
Advantages of using large blocks in breakwater construction, 179
Aëration of waves, 32
Air-slaking of Portland cement, importance of, 127, 128
Airy, Sir G. B., on tides, 44
—— ——, on waves, 23
Alderney breakwater, cost and other particulars, 216
—— ——, disturbance of rubble by waves, 201
—— ——, injurious effect of "battered" face, 207, 208
—— ——, —— mound, 30, 205
—— ——, —— parapet, 208
—— ——, method adopted in forming mound, 241
—— ——, power of waves at, 84
—— ——, sections of, 205, 206
—— ——, settlement of, 207, 276
Alexandria breakwater, 209, 210, 215, 218
Algiers breakwater, 209, 214
Algoa Bay, height of waves in, 37, 38
American rock elm, 137
Analysis and prediction of tides, 55, 56
Anchorage, good and bad, 148
Andrews, T., on corrosion of metals in sea-water, 139–141
Anemographs, 7
Anticyclones, 5, 14
Appliances for block-setting, 254
Aprons, large bags of concrete suitable for, 188
——, necessary to prevent scour, 196, 270–272
Ardrossan harbour, early use of sloping blocks at, 197
Atlantic Ocean, height of waves in, 35, 36
Atmospheric pressure, tides affected by, 57, 58

B

Bag-work, 181, 188–193, 261
——, box used for depositing bags, 189
——, frame used for depositing bags, 191
Baltic red-wood, 131, 134, 135
—— ——, creosoted, useful for sea-works, 134
Bamber on Portland cement, 124–126
Bank, Dogger, waves break upon, 28
—— of Newfoundland, waves break upon, 29
——, Riy, waves break upon, 27
Barges, 236, 245–249
—— used for constructing mound of Alderney breakwater, 241
—— —— depositing blocks pell-mell, 248, 249
—— —— depositing rubble, 245–247
—— —— laying concrete-bags, 248
Baring in quarries, 90
Barletta eastern mole, 219
Barometer, indications of, 15, 17, 19
Bars, formation of, 150–152
Batter in faces of piers objectionable, 183, 207, 208
Bay of Biscay, height of waves in, 36
Beaches, wave-action on, 41, 71, 284
Beaching-ground, 147

Beardmore on decay of iron, 143
Belcher, Sir E., on height of waves, 35
Bell Rock lighthouse, decay of iron at, 142
Benching rock in foundations, 262, 263, 265
Biarritz breakwater, 211, 215
Blasting rock, 92–94, 101–104
Blocks. *See also* Concrete blocks
——, weight of, in Colombo and Mormugão breakwaters, 196
——, ——, in Manora and Réunion breakwaters, 194
——, ——, in pell-mell mounds, 214, 215
——, ——, in stepped block-work, 213
Block-setting, 179–183, 253–255
——, appliances for, 254
Boats, fishing, description of and value, 171
Bond of block-work, 278–283
—— ——, dovetailed, 281, 282
—— ——, horizontal, 279
—— —— in Tyne piers, 283
—— ——, sloping bslock, 282, 283
—— ——, vertical, 278
Booms, 167, 233
"Bore," 61, 62
Boring rock for blasting, 96-100
Breaking waves, 26, 30
Breakwaters, classification of, 172, 173
——, cost of, 216-221
——, ——, affected by range of tide, 58-60
——, effect of falling water on roadways of, 80-82, 178
——, floating, 231–235
——, isolated, on sandy coasts, 286, 287
——, maintenance of, 216-221
——, types of, in nature, 231
——, various methods of constructing, 236-256
Breakwaters of mound type, 197–213
—— ——, cost of maintenance compares favourably with that of breakwaters of vertical type, 201
—— ——, direction of rubble-mound breakwaters should be as square to waves as possible, 202
—— ——, objection to rubble-mound type, 200
—— ——, pell-mell blocks, 208-212
—— ——, —— backed with rubble, 209, 210
Breakwaters of mound type, pell-mell blocks on rubble base, 209
—— ——, —— with superstructure, 209, 210
—— ——, rubble mound, faced and capped with pell-mell blocks, 209
—— ——, ——, faced and capped with stepped block-work, 212, 213
—— ——, —— with superstructure, the seaward slope being faced with pell-mell blocks, 211
—— ——, slopes assumed by rubble mounds at various depths, 198–200
Breakwaters of vertical type, 173, 175–197
—— ——, concrete blocks laid in horizontal courses, 179–183
—— ——, —— laid in sloping courses, 181, 193–197
—— ——, —— on base of mass-work, 183, 184
—— ——, concrete in mass, deposited within temporary frames, 183–187
—— ——, side walls of masonry, with hearting of dry rubble, 177–179
—— ——, timber-framed, 175–177
Bristol Channel, tides in, 51
Broken stone, used for levelling foundations under water, 268, 269, 273
Buys Ballot's law, 15

C

Calver, depth of wave-disturbance, 28
——, design for wave-screen, 228–230
Cape Horn, height of waves at, 35
Carey-Latham concrete-mixing machine, 117, 118
Cast iron, durability of, in sea-water, 142, 143
Catania new mole, particulars relating to, 218
Cay, Dyce, first used large bags of concrete at Aberdeen, 189
Cements, 124–131
Chain mats used at Holyhead to check movement of rubble, 202
Chalk, analysis of, 124
—— unsuitable for sea-works, 112
Charts, weather, 6, 14
Chèlura terebrans, 132, 133
Cherbourg breakwater, particulars relating to, 217

Chesil Bank, depth of wave-disturbance at, 28
Clarke, Sir Andrew, on Alderney breakwater, 208
Clay, analysis of, 124
——, founding upon, 273
Clouds, significance of, 18, 19
Coast-line, configuration of, affects winds and currents, 4
Coasts, exposure of, 73–75, 86, 88
Colombo, breakwater at, 194–196, 220
——, disturbance of rubble by waves at, 201
——, height of waves at, 74
——, settlement of breakwater at, 181, 277
Concrete, bag-work, 181, 188–193, 261
——, early use of, 113
——, made with hydraulic lime, 114, 115, 119, 120
——, made with Roman cement, 122,123
——, mass-work, 183–187
——, ——, in under-water foundations, 262–264, 266–268
——, mixing by hand and by machines, 116
—— mixing machines, 116–118
——, proportions of ingredients, 115, 119–123, 185, 187, 191
Concrete blocks, advantages of using large, in breakwaters, 179
——, moulds for making, 118–119
——, proportions of ingredients in, 119–122
—— should be laid as "headers," 183, 279
—— should not be stacked, or used in work, when too "green," 122
——, stone faced, 123
——, weight of, in Colombo and Mormugão breakwaters, 196
——, ——, in Mancra and Réunion breakwaters, 194
——, ——, in pell-mell mounds, 214, 215
——, ——, in stepped block-work, 213
Considerations affecting design of harbours, 146–149
Contours of sea-bed affect direction of waves, 74
Coode, Sir John, concrete-mixing machine, 116
——, ——, on depth of wave-disturbance, 28
Coode, Sir John, on injurious effect of mound of Alderney breakwater, 205
Copper sheathing, used for protecting timber, 134
Corrosion of iron in sea-water, 139–145
Cost of breakwaters, 216–221
Cranes. *See* Setting-machines
Creosoted timber, useful for sea-works, 134
Crests upon waves, how formed, 31
Cuba hurricane, diagram of, 5
Currents, 63–72
—— affect height of waves, 71, 72
——, effect of wind on, 67, 68
——, littoral, misconception concerning, 71
——, ——, velocity of, increased by breakwaters projected across them, 70
——, origin of, 63
——, scouring power of, 160
—— sometimes run counter to prevailing winds, 68, 69
——, strong, across harbour entrances objectionable, 159
——, ——, out of harbours objectionable, 72, 160
——, temporary, sometimes caused by wind, 68
Curved profiles for sea-walls, 205, 207, 271
Cyclones, 5, 14. *See* also Gales, Hurricanes, Storms
——, rate of progress of, 6, 7
——, typical diagram of, 6

D

Damage to sea-works often greatest when gale is subsiding, 32
Danger of open joints in sea-works, 107–109, 207, 243, 244
Decay of iron, 139–145
—— of rocks, 105, 111, 112
Declination of sun and moon affects tides, 48–50
Deep water, value of, at harbour entrances, 159, 168–170
De Horsey, Admiral, on height of waves, 36
Depth of water affects height and character of waves, 25
Depths to which wave-action is felt, 27–29, 201, 202

Design of ground-plans of harbours, 152–160, 169
Destructive effect of falling water, 80–82, 178
Diagrams, strength of Portland cement, 129
——, tidal, 53, 54
——, wind, 2, 3
——, wind velocities and pressures, 11
Difficulties attending the execution of work near low water, 259–261
—— connected with rock foundations, 261–265
"Dip" and "strike" of strata should be utilized in quarrying, 92
Diving, 255
Dogger Bank, waves break upon, 28
Double tides, 53, 54
Douglass, Sir J. N., on the mooring of light-vessels, 234, 235
——, ——, on wave-power, 85, 86
Dover, Admiralty Pier, cost and other particulars, 219
—— ——, current past end of, 71
—— Straits, tidal current through, 69
Dove-tailed bond, 281, 282
Dowels. *See* Joggles
Dredging generally necessary at harbour entrances, 153, 285
——, rock, 154
Drift, littoral, chiefly due to wave-action, 71
——, ——, influenced by wind, 1, 20
Drifting sand, methods of arresting, 20–22
Drills for rock-boring, 99, 100
Dry bedding of blocks objectionable, 181, 182, 244, 278
Duff on value of herring fisheries, 170
Dunraven, Lord, on height of waves, 35
Dynamite, useful in preparing rock foundations, 262
——, —— in quarrying, 101

E

Earthquakes, waves caused by, 33
Earth's crust, movement of, 76–78
Electricity, firing charges by, 103
Elm, American rock, 137
Entrances of harbours, 153–164, 168
—— ——, direction of, 155, 159, 167
—— ——, forms of, 156, 157, 159
Entrances of harbours, position of, 153, 154, 162–164
——, ——, tidal or "barred," inconvenient and dangerous, 168
——, ——, width of, 159–161
Equinoctial tides, 49
Erosion caused by loose joggles, 280
—— of rocks, 105–109
Establishment, tidal, 55
Estuary harbours, 150–154
Evaporation from surface of ocean, 65
——, ocean currents affected by, 65, 66
Experiments on waves, 23, 24
Explosives used in quarrying, 101
Exposure affected by scour during gales, 75
——, effective, 73
——, general remarks on, 88
——, how to estimate, 37, 73–75
——, mud as an indication of, 86

F

Falling water, effect of, on roadways of breakwaters, 80–82, 178
Fetch alone no indication of exposure, 73
——, definition of, 73
——, effective length of, limited by extent of storms, 73
Firing charges in quarrying, 103, 104
Fish deteriorate when boats are delayed, 168
Fishery harbours, 165–171
—— ——, berthage, 169
—— ——, difficulty of designing, 165
—— ——, effect of "range" in, 165–167
—— ——, quay space, 169
—— ——, vertical type of breakwater suitable for, 167
—— ——, water area required for give number of boats, 169
Fishing boats and gear, value of, 171
Floating breakwaters, 231–235
—— ——, impossibility of mooring, 232, 234
Forced waves, 33
Forecasting weather, 6, 14, 19
Foreshores, advance of, 285
Forth bridge, wind-gauges at, 9
Foundations, 257–274
——, bag-work, 181, 188–193, 261
——, benching rock, 262, 263, 265
——, mass-work, 262–264, 266–268

Foundations, small stone used for levelling, 268, 269, 273
Founding upon clay, 273
—— —— gravel, 273
—— —— mud, 271, 272
—— —— rock, 257–270
—— —— rubble, 273, 274
—— —— sand, 270, 271
Fraserburgh breakwater, 192, 220
Free waves, 33
Fundy, tidal range in Bay of, 51
Fuses for firing charges in quarrying, 103, 104

G

Gales. *See also* Cyclones, Hurricanes, Storms, etc.
——, course of, 16
——, extent of, 5–7
——, forecasting, 14
——, list of, in Britain, with velocity over 80 miles per hour, 12
——, progress of, 6, 7
——, relative frequency of, on British coasts, 13
Gambia, s.s., rate of corrosion of plates, etc., 141, 142
Genoa new mole, particulars relating to, 216
Gradient, barometric, 14, 15
Granite suitable for sea-works, 111
——, weight of, 110
Gravel, founding upon, 273
Greenheart, 131, 134–136
—— attacked by sea-worms, 135
—— suitable for sea-works, 136
Ground plans of harbours, 152–160, 169
Ground swell, 33, 34
Grouting, 268, 269
Gulf Stream affects course of storms, 68

H

Halos, significance of, 19
Harbours, considerations affecting design of, 146–149
——, fishery, 165–171
——, ground plans of, 152–160, 169
——, no general rules can be laid down for design of, 146
—— on sandy coasts, 286, 287
Harbours of refuge, requirements they should fulfil, 148, 149
Harcourt, Vernon, description of Alderney breakwater, 30, 276
Hawkshaw, Sir John, on failure of Alderney breakwater, 207, 208
Hays, design for wave-screen, 225–227
Hayter, Harrison, on Holyhead harbour and quarries, 95
Headers, blocks in breakwaters should be laid as, 279
Hearting, danger of loose rubble, 178, 179, 207
Height of waves, 12, 34–39, 74
Hercules. *See* Setting-machines
Herring fisheries, description and value of boats employed in, 171
—— ——, value of, 169, 170
Holburn Head, power of waves at, 80–82
Holding-ground, 148
Holyhead breakwater, effect of mound upon waves, 31
—— ——, head of, 223
—— ——, mode of depositing rubble in mound, 240, 241
—— ——, particulars relating to, 216
—— ——, slopes assumed by mound, 198, 199
—— ——, staging, 238, 240, 245
——, quarrying at, 92–96
Horizontal bedding of block-work, 179–181, 278, 279
Hurricane, great Cuba, diagram of, 5
——, of November, 1893, description of 10–12

I

Icebergs act as floating breakwaters, 231
——, waves break against vertical faces of, 174
Impact of waves (*see also* Power of waves), 26, 40
Iron, 138
——, corrosion of, in sea-water, 139–145
——, preservation of, 144
Ironwood, 131, 137
Isobars, 14
Isolated breakwaters on sandy coasts, 286, 287

J

Jarrah, 131, 134, 137
——, very liable to split, 137
Joggles, 279, 280, 283
——, danger of loose, 280
—— in under-water work, 280

Joints, danger of open, in sea-works, 107–109, 207, 243, 244
Jura Sound, "race" through, 70

K

Kelvin, Lord, analysis and prediction of tides, 55
Kilrush pier, 178
Kingstown breakwaters, 198, 217
Kinipple, W. R., on grouting under-water foundations, 270
—— ——, on St. Helier's breakwater, 269
Krakatoa, waves caused by eruption of, 33
Kurrachee, height of waves at, 74
——, setting-machine used at, 194
——, storms unknown at, 74

L

Leghorn curvilinear mole, particulars relating to, 218
Length of waves, 26–29, 32, 33
Lights for pier-heads, 224
Lime, failure of mortar in Holyhead breakwater, 114
—— used in sea-works, 114, 115, 119, 120
Limnoria terebrans, 132
Littoral currents, misconception concerning, 71
Littoral drift, chiefly due to wave-action, 71
Low-water work, often tedious and costly, 260
Luna rainbows, significance of, 19

M

Madras breakwaters, disturbance of rubble by waves, 202
Maintenance of breakwaters, cost, 216–221
Mallet on preservation of iron, 144
Mammoths. *See* Setting-machines
Manora (Kurrachee) breakwater, 194, 220
—— ——, absence of bond in, 282
Marseilles (La Joliette) breakwater, 210, 215
Mass concrete, 183–187. *See also* Concrete
——, foundations under water, 262–264, 266–268
Mass-concrete, protecting surface of, from fretting action of waves, 258–260
Materials, 105–145
——, selection of, for sea-works, 105
Maury, waves caused by earthquake at Simoda, 33
Medina cement, properties and uses of, 122, 123, 131, 258, 259
Mediterranean Sea, circulation of water in, 67
—— ——, tides in, 52
Messent, bond in Tyne breakwaters, 283
——, concrete-mixing machine, 117
—— on Roman cement concrete used in Tyne piers, etc., 123
Methods of constructing breakwaters, 236–256
Model of sea-bed, useful in dealing with under-water rock foundations, 261
Molony, Capt., on height of waves, 36
Monolithic work, 183–187. *See also* Concrete and Mass-concrete
—— ——, breakwater formed entirely of, 192
Monsoons, 16, 17
Moon, tides produced by, 45
——, tide-producing power of, 46
Mormugão breakwater, 194–196, 215, 221
Motion of particles in waves, 23–28
Mounds of breakwaters. *See also* Breakwaters of mound type
—— ——, effect of, upon waves, 29–31, 205
—— ——, level up to which they should be carried, 202
—— ——, modes of constructing, 236–249, 255, 256
—— ——, pell-mell blocks, 208–212
—— ——, slopes assumed by rubble, 198–200
Mud as an indication of exposure, 86
——, founding upon, 271, 272
Murray, on depth to which wave-action extends, 29

N

Naples, S. Vincenzo mole, 218
Neap tides, 46, 52
Newfoundland, bank of, waves break upon, 29
Newhaven (Sussex) breakwater, 188, 220
Notching of face-blocks, 280

O

Oak, 131, 134, 136
Ocean currents, 63
Open joints, danger of, in sea-works, 107–109, 207, 243, 244
Orbits of particles in waves, 23–28
Oregon pine, 131, 136
Oscillatory waves, 24–28
Overburden in quarries, 90
Over-end tipping, mound breakwaters constructed by, 255
Oxidation of iron in sea-water, 139–145

P

Parapets, injurious effect of, 208
——, use of, 148
Parkes on damage to Wick breakwater, 84
Particles, movement of, in waves, 23–28
Pell-mell block breakwaters, 208–212
—— —— ——, stability of blocks in, 214, 215
Pentland Frith, current through, 69
Period of waves, 26
—— ——, caused by earthquakes, 33
Peterhead, early use of sloping block masonry at, 197
——, ground plan of harbours, 166
——, height of waves at, 35, 39
Pholas dactylus, 112, 132
"Piano-blocks," used in Tyne breakwaters, 283
Piers. *See* Breakwaters
Pier-heads, current liable to undermine or erode, 71
——, various forms of, 222–224
Pierres perdues block mounds, 208
Pile-work foundation for breakwaters, 272
Pitch-pine, 131, 136
Plymouth breakwater, 198–200
—— ——, effect of discarding small rubble, 203
—— ——, —— of pitching slopes, 200
—— ——, particulars relating to, 217
Port Erin breakwater, 208, 214
Port Said, advance of foreshore at, 285
—— —— breakwater, 208, 214
Portland breakwater, cost of staging, 245
—— ——, particulars relating to, 216
Portland cement, analysis of, 129
Portland cement, core in, an element of danger, 127
—— ——, importance of thorough air-slaking, 127
—— ——, indications of good, 128
—— ——, process of making, 124–126
—— ——, setting of, 128–130
—— —— should be finely ground, 127
—— ——, specific gravity of, 128
—— ——, strength of, 128, 129
Precipitation, ocean currents affected by, 66
Preliminary investigation of proposed harbour sites, 146
Pressure of wind, relation of, to velocity, 7–12
Progress, average rate of, in constructing various breakwaters, 216–221
Proportions of ingredients for concrete, 115, 119–123
Puzzuolana, injurious effect of at Holyhead, 114
—— used in concrete, 114, 120

Q

Quarrying, 89–104
——, arrangement and working of quarries, 91, 92
—— at Holyhead, 92–96
——, blasting, 92–94, 101–104
——, drainage of quarries, 90
——, drilling holes for charges, 96–100
——, explosives used in, 101
——, overburden, 90
—— plant, 94, 95
——, seam-firing, 101
——, selection of quarry site, 89
——, "strike" and "dip" of strata, 92

R

"Races" or "roosts" of the tide, causes of, 69, 70
Range of tides, 51–54
—— in harbours, 165–167, 222–224
Redman on decay of iron, 144
Reduction of waves, 161, 162
Refuge harbours, 148, 149
Reid on storms, 5, 19
Revenue, success or failure of works often depends upon, 286

Riy Bank, waves break upon, 27
Roadsteads, 157, 158, 163
Roadways of breakwaters, effect of falling water upon, 80–82, 207
Rock, benching, under water, 262, 263, 265
——, blasting, 92–94, 101–104
——, boring, 96–100
——, foundations, 257–270
Rollers arriving before gale, 19
——, direction of, 34, 74
Roman cement concrete, 122, 123
—— ——, properties and uses of, 122, 123, 130
—— ——, strength of, 130
Rubble, danger of, as hearting, 177–179, 207
——, depths to which disturbed by wave-action, 201, 202
——, founding upon, 273, 274
——, injurious effect of discarding small, in constructing Plymouth breakwater, 203
——, levelling up rock foundations with, 270
——, modes of depositing, in mounds, 202, 240, 241, 244–246
——, settlement of, in mounds, 207, 275–278
——, slopes assumed by, in mounds, 198–200
——, space occupied by, in mounds, 204
Rubble mounds of breakwaters injuriously affect character of waves, 29–31, 205
Russell, Scott, experiments on waves, 23, 24

S

St. Heliers (Jersey) landing-pier, damage to, 178
St. Jean de Luz (Artha breakwater), 209, 210, 215
Sand, bags of, useful in foundation work, 259, 261
——, founding upon, 270, 271
Sand-blast, 107
Sand-drifts, 20
——, methods of arresting, 21, 22
Sandy coasts, harbours on, 286
Sartorius, Admiral Sir G. R., on floating breakwaters, 233, 234
Saxicava, 112
Scoresby on height of waves, 36
Scott, design for wave-screen, 228
Scour during gales affects exposure, 75
Scouring power of currents, 160
Screens. *See* Wave-screens
Scupper-nailing, 134
Seam-firing in quarries, 101
"Send" of vessels should be allowed for in determining depth at harbour entrances, 154
Setting concrete blocks, 253–255
Setting-machines, exceptionally large, used at Leixoes, 237
——used at Colombo, Mormugão, and Kurrachee, 194, 251
——, various types of, described, 250–253
——, weight of, causes settlement in work, 181, 276
Settlement, 180, 181, 275–278, 283
——, caused by weight of "Titans," or setting-machines, 181
——, —— —— ——, breakwater superstructures, 275–277
—— of Alderney breakwater, 207, 276
—— of Colombo breakwater, 181, 277
—— of Holyhead breakwater, 276
—— of horizontally coursed work, 277
—— of Manora breakwater, 277, 282
—— of Mormugão breakwater, 277
—— of sloping block-work, 276, 282, 283
—— usually greatest in breakwaters of mound type, 275
Shelter, degree of required, affects design and cost of breakwaters, 147, 148
Shingle, eroding power of, 106, 107
Silting, 284–288
—— causes advance of foreshores, 285
——, process of, 284
—— under lee of isolated breakwaters, 287
Simoda, waves caused by earthquake at, 33
Slag from iron furnaces, specific gravity of, 113
—— —— used for constructing breakwaters, 113
Sleat Sound, "race" through, 70
Slipways, 168
Sloping-block system of construction, advantages of, 181, 194, 197

Sloping-block system of construction, bond in, 282, 283
—— —— ——, early use of, 197
—— —— ——, work very little affected by settlement, 282, 283
Sluicing, 286
Small broken stone used for levelling foundations, 268, 269, 273
Smith, W., on Aberdeen south breakwater, 182, 243, 244
Sneezewood, 132, 134, 137, 138
Southampton, double tide at, 53, 54
Spending-beaches, 147, 155, 167
Spring tides, 46
Stability of blocks thrown together pell-mell, 214, 215
Staging, 236–245
——, Aberdeen south breakwater, 241
——, Alderney breakwater, 241
——, chain stays for, 243
——, cost of, 245
——, facilities afforded by, 237, 244, 245, 264, 265
——, height of, 241
——, Holyhead breakwater, 238, 242
——, need not extend whole length of work, 244
——, ordinary sea, 239
Steel, consumption of, in quarrying, 99
——, corrosion of, in sea-water, 139, 140
Stepped blockwork, 212, 213
Stevenson, Thomas, on height of waves, 36, 37
——, ——, on power of waves, 82
——, ——, on reduction of waves, 161, 162
Stone, 110–113
—— attacked by *Pholas dactylus* and *Saxicava*, 112
——, decay of, 111, 112
—— for sea-works should have high specific gravity, 110
——, weight of various kinds, 110, 111
Stoney, B. B., system of constructing breakwaters, 187
Storm centre, position of, 15
Storms, course of, 16
——, direction of, affected by Gulf Stream, 68
——, extent of, 5
——, rate of progress of, 6, 7
"Strike" and "dip" of strata should be utilized in quarrying, 92
Stroke of wave, greatest just as wave begins to break, 26, 40, 41
Sun, tides produced by, 45
——, tide-producing power of, as compared with that of moon, 45, 46
Sunken reef or shoal, effect of, on waves, 27–29
Superstructure, effect of placing, upon rubble mound, 201
Survey of site of proposed harbour, 146, 147
Swell, direction of, 34
—— preceding storms, 19, 34
Synoptic charts, 6, 14

T

Table Bay breakwater, 198, 200
"Tabling," 282
Tamping bore-holes in quarrying, 102
Teak, 131, 134, 136
Telford, early use of sloping block masonry by, 197
Temperature of ocean, 64
—— rises on approach of storms, 17
Temple of Jupiter Serapis, movement of ground at, 77
Teredo gigantea, 133
—— *navalis*, 132–138
Thomson, Sir Wm., analysis and prediction of tides, 55
——, Sir Wyville, on evaporation and precipitation, 66
——, ——, on temperature of the ocean, 64
Tidal currents, 50, 51, 69, 70
—— —— affect depth of water at harbour entrances, 72
—— —— affect sea-works more than ocean currents, 69
—— —— affect width of harbour entrances, 72, 160
—— —— at Kyle Rhea, 70
—— —— past harbour entrances, 70
—— —— through Pentland Frith, 69
—— —— through Straits of Dover, 69
—— —— through Sound of Jura, 70
—— ——, velocity of, increased by breakwaters projected across them, also by headlands, 70
Tidal curves or diagrams, 53, 54
—— establishment, 55

Tidal harbours, 60
—— harmonic analyzer, 55
—— range, 51–54
—— —— affects cost of breakwaters, 58–60
—— ——, work within, 258–261
—— wave affected by distribution of land, etc., 47
—— ——, progress of, 50, 51
Tides, 44–62
—— affected by variations in distance of sun, moon, and earth from each other, also by declination, 48
——, analysis of, 55, 56
——, benefits derived from, 60, 61
——, difference of range in summer and winter, 49
——, diurnal and semi-diurnal, 49
——, double, 53, 54
——, effect of atmospheric pressure upon, 57, 58
——, effect of wind upon, 56, 57
——, equinoctial spring, 49
——, neap, 46, 52
——, normal rise of, in open ocean, 52
——, prediction of, 55, 56
——, priming and lagging of, 48
——, range of, 51–54
——, ——, affects cost of breakwaters, 58–60
——, spring, 46, 52
——, theory of, 45
Timber, 131–138
——, destruction of, by sea-worms, etc., 132–138
——, different kinds used in sea-works, 131
——, protection of, 134
"Titans," or setting-machines, at Colombo, Kurrachee, and Mormugão, 194
——, ——, various types described, 250–253
——, ——, weight of, causes settlement in work, 181
Translation, waves of, 25, 26, 29. *See also* Waves

V

Value of fishing boats and gear, 171
—— herring fisheries, 169, 170
Various methods of constructing breakwaters, 236–256
Velocity of littoral currents accelerated by piers projected across them, 70, 71
—— waves, 32, 33
—— wind, relation of, to pressure, 7–12
Vernon-Harcourt, description of Alderney breakwater, 30, 276

W

Water, circulation of, in Mediterranean, 67
——, depth of, affects waves, 25, 29
——, destructive effect of falling, 80–82, 178
——, quantity of, used in mixing concrete, 115, 116
Wave-breaker, 193
—— —— at Mormugão, 195, 196
—— —— at Ymuiden, 271
—— —— proposed for Alderney breakwater, 208
Waves, 23–43
——, action of, against vertical face, 173, 174
——, ——, on beaches, 41, 71, 284
——, aëration of, 32
—— assist in forming bars at mouths of rivers, 152
—— breaking, 26, 30
—— caused by earthquakes, 33
——, character of, affected by depth of water, 25, 29, 205
——, crests of, how formed, 31
——, depth of disturbance caused by, 28, 29, 201, 202
——, direction of, influenced by contours of sea-bed, 74
——, experiments on, 23, 24
——, forced, 33
——, force of (*see also* Power of waves), 26, 40, 41, 78–86
——, free, 33
——, generation of, 1
——, ground-swell, 33, 34
——, height of, 12, 34–39, 71, 72, 74
——, impact of, 26, 40, 41
—— injuriously affected by breakwater mounds, 29, 205
——, length of, 26–29, 32, 33
——, motion of, 24
——, movement of particles in, 23–28
—— of oscillation, 23–28
—— of translation, 26, 29

Waves, period of, 26, 33
——, power of, may be over-estimated, 75–80
——, ——, at Alderney, 84
——, ——, at Bishop Rock, 85
——, ——, at Bound Skerry, 82
——, ——, at Dhu Heartach lighthouse, 84
——, ——, at Fastnet Rock, 85
——, ——, at Holburn Head, Caithness, 80–82
——, ——, at Manora breakwater (Kurrachee), 84
——, ——, at Scilly Isles, 86
——, ——, at Wick, 84
——, ——, at Wolf Rock, 86
——, ——, at Ymuiden (Holland), 83
——, ——, on coast near Wick, 78, 79
—— reduced in height by crossing shoals, 32
——, reduction of, in harbours, 161, 162
——, theory of, 23
——, velocity of, 32, 33
——, wheeling of, 74, 75
Wave-screens, 225–231
Weather charts, 6, 14
Weber, experiments on waves, 23
Weed-fields act as floating breakwaters, 231
Weight of blocks used in breakwaters, 194, 196, 213–215
—— of breakwater superstructures causes settlement, 275
—— of setting machines causes settlement, 181, 276
Wick breakwater, failure of, 178
Width of harbour entrances, 159–161
Willet on proportions of ingredients for concrete, 121, 122
Wind, 1–22
—— diagrams, 2, 3
——, direction of, influenced by trend of coast, 4
——, effect of, on currents, 67, 68
——, ——, on tides, 56, 57
——, force of, varies with barometric gradient, 14, 15
—— gauges, 7, 9
——, harbour entrances affected by, 20
——, indications of, 19
——, influence of, on littoral drift, 1, 20
——, "jumping" of, 16
——, relation of velocity to pressure, 7–12
——, temporary currents caused by, 68
——, the generator of sea-waves, 1
——, theory of, 4
Worm. See *Teredo*, *Limnoria*, *Chèlura*
Wrought iron, corrosion of, in sea-water, 139–144

Y

Ymuiden harbour, current past entrance, 70, 160
—— ——, dredging at, amount of and cost, 285
—— ——, power of waves at, 83
—— ——, stability of blocks in wave-breakers, 215
—— ——, width of entrance, 160
Young, Archibald, on harbour accommodation for fishing-boats, 169, 170

PRINTED BY WILLIAM CLOWES AND SONS, LIMITED, LONDON AND BECCLES.

UNIVERSITY OF TORONTO
DEPARTMENT OF CIVIL ENGINEERING
Municipal and Structural

SIA-218

PLEASE DO NOT REMOVE
CARDS OR SLIPS FROM THIS POCKET

UNIVERSITY OF TORONTO LIBRARY

S&M
A
218

UNIVERSITY OF TORONTO
DEPARTMENT OF CIVIL ENGINEERING
Municipal and Structural